

RD-A122 015

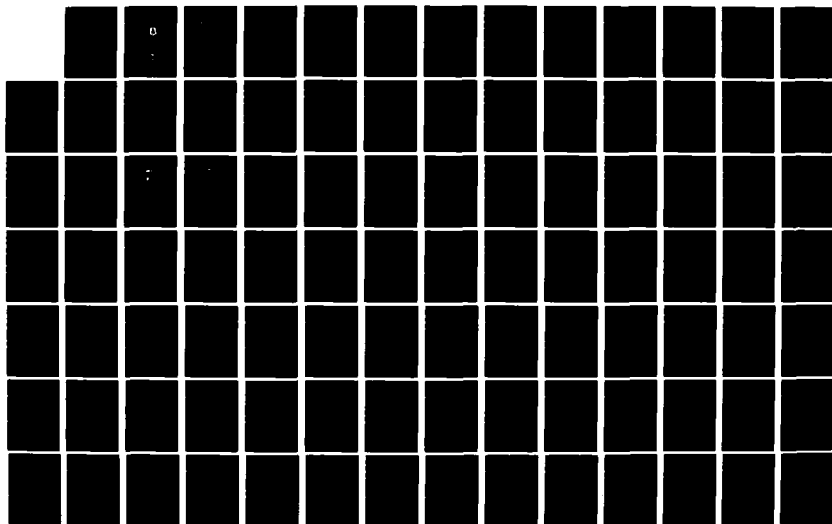
MODERN SCIENCE TECHNOLOGY SERIES MEASUREMENT OF
BALLISTICS(U) FOREIGN TECHNOLOGY DIV WRIGHT-PATTERSON
AFB OH C YEEMING 27 OCT 82 FTD-ID(RS)T-1071-82

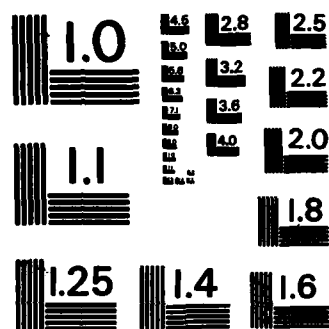
1/2

UNCLASSIFIED

F/G 19/4

NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AD A122015

FTD-ID(RS)T-1071-82

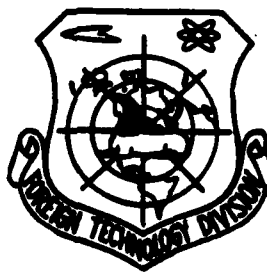
FOREIGN TECHNOLOGY DIVISION



MODERN SCIENCE TECHNOLOGY SERIES
MEASUREMENT OF BALLISTICS

by

Chen Yeeming



DTIC
ELECTE
DEC 2 1982
A

Approved for public release;
distribution unlimited.

DTIC FILE COPY

82 12 02 077

EDITED TRANSLATION

FTD-ID(RS)T-1071-82

27 October 1982

MICROFICHE NR: FTD-82-C-001372

MODERN SCIENCE TECHNOLOGY SERIES MEASUREMENT
OF BALLISTICS

By: Chen Yeeming

English pages: 94

Source: Dandao de Oeliang, 25 August 1978,
4 unnn pgs; 1-88

Country of origin: China
Translated by: SCITRAN
F33657-81-D-0263

Requester: NSA/AFSCLO
Approved for public release; distribution unlimited.

THIS TRANSLATION IS A RENDITION OF THE ORIGINAL FOREIGN TEXT WITHOUT ANY ANALYTICAL OR EDITORIAL COMMENT. STATEMENTS OR THEORIES ADVOCATED OR IMPLIED ARE THOSE OF THE SOURCE AND DO NOT NECESSARILY REFLECT THE POSITION OR OPINION OF THE FOREIGN TECHNOLOGY DIVISION.

PREPARED BY:
TRANSLATION DIVISION
FOREIGN TECHNOLOGY DIVISION
WP-AFB, OHIO.

GRAPHICS DISCLAIMER

All figures, graphics, tables, equations, etc. merged into this translation were extracted from the best quality copy available.

[illegible]

FOREWORD

The measurement of ballistics is a very much involved, rapidly developing new technological science. It involves all the areas in radio, and also involves optics, mechanical engineering, and ground measurement. Furthermore, it involves the study of mathematical treatment. Hence, if we wish to use a small volume like this to describe its contents in order to popularize this newly developed technological science, it is going to be difficult to fulfill this purpose based on the level of the author and the limited space and depth of discussion. Through this little volume, if the readers can be inspired to generate some interest in this new science and take a step further to study harder, then the initial basic objective of this book is accomplished.

In order to explain certain problems more clearly, it is necessary to use some mathematical equations. These formulas are taught in high school and they are useful in the understanding of the basic knowledge in this book.

Due to the limited level of the author, it is unavoidable to have errors and shortcomings in the book. The suggestions and criticism from the readers are sincerely welcome. They will be used as a basis for future corrections.

The Author
1978.8.25

INDEX

| | | |
|-----|---|----|
| I | INTRODUCTION | 1 |
| II | Major Applications of Electronic Ballistic Measuring Systems | 4 |
| | Speaking of parabolic motion | 4 |
| | The "Cannon" without a barrel - missile | 5 |
| | How to increase the accuracy of missiles | 9 |
| | How do satellites enter orbits | 11 |
| | Multi-target measurement | 12 |
| | How to retrieve satellites | 14 |
| | How to ensure safety in test areas and flight zone | 15 |
| III | Some Basic Concepts of the Electronic Ballistics Measurement System | 16 |
| | Radiowave, frequency and phase | 16 |
| | Propagation of Radiowave | 20 |
| | Carrier Wave, Signal and Modulation | 25 |
| | Distance Measurement Signals | 28 |
| | Demodulation of Signals | 33 |
| | Geometric Principles of Determination of Position for Target in Space | 35 |
| | Mathematical Expressions of Velocity and Position of Spatial Targets | 39 |
| | Basic Requirements of the Electronic Ballistics Measurement System | 40 |
| IV | Basic Composition of an Electronic Ballistics Measurement System | 41 |
| | Coordinative Targets and Transponder | 41 |
| | Antenna and the Capturing and Tracking of Targets | 43 |
| | The Transmitter | 47 |
| | The Receiver | 48 |
| | The Terminal | 51 |
| | Data Transfer and Data Processing | 53 |
| | Schematic of the Composition and Working Procedures | 55 |

| | | |
|------|---|----|
| V | The Doppler Velocity Measurement and Position Determination System | 56 |
| | Doppler Effect | |
| | How to Measure Velocity | 58 |
| | How to Determine Position | 61 |
| VI | The Phase Comparison Measurement System | 64 |
| | Principle of Angle Measurement using Phase Comparison | 64 |
| | How to Determine Position | 67 |
| | How to Measure Velocity | 69 |
| VII | The Multiple Station Measurement System | 71 |
| | Principle of Continuous Wave Distance Measurement | 71 |
| | Principles of Position Determination and Velocity Measurement Characteristics | 73 |
| VIII | How to Increase the Accuracy of Measurements | 75 |
| | What is Measurement Error | 75 |
| | Ground Survey Error | 79 |
| | Wave Refraction Error | 80 |
| | Instrumentation Error | 83 |
| | Time, Light Speed Error | 84 |
| | Combined Use of Data and Data processing | 85 |
| IX | Outlook of Electronic Ballistics Measurement Systems | 87 |
| | The Establishment of Measurement and Control Network | 87 |
| | Data Relaying Satellite System | 88 |
| | Measurement of Cruise Missile | 90 |
| | Measurement of Re-entry Section | 92 |
| | Closing Remarks | 93 |

II MAJOR APPLICATIONS OF THE ELECTRONIC BALLISTICS MEASUREMENT SYSTEM

/4

Speaking of Parabolic Motion

We have seen the grenade throwing contest in an athletic event. The athletes waved their thick arms to throw the grenades to sixty, sixty-five --- meters away to show their best effort in front of a crowd. The people praised them saying "it's really tough." In order to obtain good results, the athletes paid a tremendous price by hard work training. Don't you forget that

these accomplishments also include the hard work of the coaches. They repeatedly corrected the throwing posture of the athletes with emphasis on "fast release." Why?

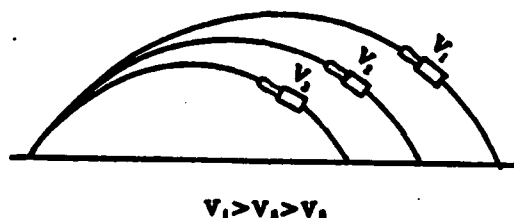


Figure 2.1. Relationship between throwing distance and velocity.

The reason for this has been learned in physics. When we throw an object at a fixed projectile angle, the higher the initial velocity of the projectile the farther the throw becomes. We can use Figure 2-1 to explain this problem. Similarly, when the initial speed is the same, the distance of the throw is related to the projectile angle. The throwing distance is getting longer when the projectile angle becomes larger up to a 45° projectile angle at which the distance is the maximum. Continuing increasing the projectile angle from there on, the throwing distance decreases with increasing projectile angle. Figure 2-2 explains this pro-

/5

cess. Therefore, in order to throw the grenade farther, two conditions must be satisfied: first, the initial speed must be high which means the release must be fast; second, the throwing projectile angle must be proper. The ideal angle is 45° . This requires an accurate posture.

Regardless whether it is a grenade or shell from a cannon, or even a modern missile, these objective principles must be met.

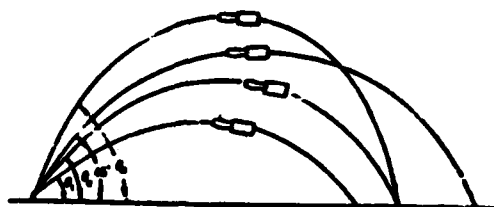


Figure 2-2. Relationship between throwing distance and angle.

The "Cannon" Without a - Barrel - Missile

In the grenade throwing contest, the one who reaches the farthest distance becomes number one. However, in actual combat, it is not enough just to throw it the farthest. It must be thrown accurately to explode over the enemy's head. The same thing applies to cannons. Before firing against the enemy, the commander gives the order "target, dead ahead, distance, 5000, commence firing." The liberation army soldiers then tensely adjust the angle of the gun according to the order of the commander. Shells begin to accurately fall in front of the enemy line to defeat the enemy.

For those with rifle firing experience, they know that the indicator on the rifle must be adjusted according to the target distance. These measures are necessary for the accurate hitting of the targets. What are the reasons for them?

As we all know, the motion of an object tossed upward can be /6
 considered as the combination of two motions. One is a uniform
 linear motion based on the initial velocity V_0 and the other is
 the vertically downward free falling body motion due to gravity.
 According to these principles, we can obtain the curve shown in
 Figure 2-3.

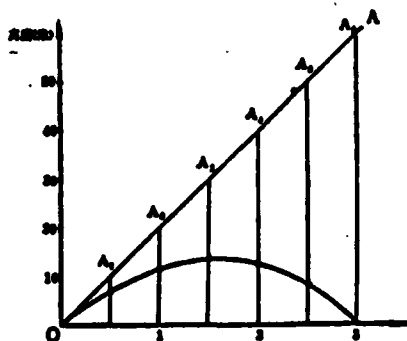


Figure 2-3. Trajectory Curve.
 Key: (1) Height (m); (2) time (sec);

Let us assume that a projectile is launched slanted upward
 at a certain initial speed and projectile angle. Based on the
 reasons stated before, the object on one hand must travel along
 the OA direction in a uniform speed linearly to reach A_1 at the
 end of the first second, A_2 at the end of the second second,
 while on the other hand under gravity it must fall by 4.9 m in
 distance at the end of the first second, and 19.6 m at the end
 of the second second ----. If we divide the time into very
 small segments, then a new curve can be obtained. The new curve,
 starting from the beginning of the throw until it reaches the
 ground, forms a parabola. This is a trajectory curve. The
 motion of any projectile follows this law of motion.

The trajectory curve described above is a theoretical curve /7
 which does not take the friction of air into consideration.

However, ordinary shells must travel in air. The higher the speed of the motion, the larger the air friction becomes. At this time the trajectory will vary. Using the 85 mm cannon as an example, if the projectile angle is 30° , its range is 56 kilometers based on the theoretical trajectory when there is no air friction. However, actually the range is only 15 kilometers. This shows that there is a great difference between theoretical and actual trajectories. Through this example, we raise two problems: (1) how to better control the projectile angle of the cannon in actual combat in order to more accurately hit the target. (2) How to solve the problem of increasing the range of the shells. Since the effect of air friction is so large, it is very difficult to increase the range by increasing the initial velocity alone. Because of the objective of increasing the range, the initial velocity is increased. However, the resistance of the shell is also significantly increased by increasing the initial velocity. Hence, the expected result of longer range is not obtained.

Before issuance, each new type of cannon must be tested many times. Once the loading of charge is fixed, the initial speed of the shell is predetermined. The above tests are to determine a "firing table" for this cannon based on the relation between range and projectile angle obtained in actual practice. This "firing table" informs the soldiers about the various projectile angles which ought to be used under different range and natural conditions. This is very similar in principle to the "indicator" adjustment on a rifle.

On the basis of scientific technological development, various types of ballistic missiles have been developed. Ballistic missiles are launched differently from ordinary cannons. When a missile is launched, it is placed vertically on the launching pad. After ignition, the missile is gradually lifted upward (see the OA segment in Figure 2-4). After reaching a certain altitude,

the control system makes the missile tilt towards the target. Due to the consumption of fuel, the weight of the missile decreases. At this time, the missile has already passed the dense atmosphere. The thrust is getting bigger, the weight of the missile is becoming lighter, and the velocity is getting higher. Thus, the paradox between velocity and air friction is resolved. Figure 2-4 is the schematic diagram of the trajectory of a missile during launch and operation. When the missile reaches a certain position (point C in Figure 2-4), and a predetermined speed, the computer in the missile will order an "engine shut-off" command based on a pre-arranged program to separate the warhead from the carrying rocket. This instance is very similar to that of a shell leaving the muzzle of a cannon. The head of the missile, based on the initial velocity reached by the thrust of the engine before its shut-off, flies to the target accurately according to the predetermined trajectory. /8

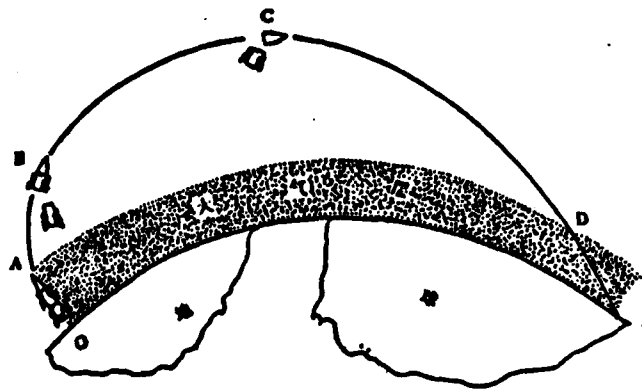


Figure 2-4. Schematic Diagram of Missile Operating Ballistics.
Key: (1) Vertical upward section; (2) First rocket working; (3) Second rocket working; (4) Free motion section; (5) Re-entry section; (7) Earth.

From the above simple introduction, a missile is actually a cannon without a barrel. But, it can also be considered as having an invisible barrel which is very very long, from the ground launching pad extending to the instance that the "shut-off" order is given. It can be on the order of 100 or several hundred kilometers long. However, it is not visible to the naked eye.

How to Increase the Accuracy of Missiles

We mentioned before that before issuing the cannons to the soldiers, in order to gain higher accuracy a "firing table" must be compiled based on actual real-shell firing tests. The missile is a special cannon which also requires a "firing table" to make it hit farther away more accurately. However, this "firing table" is stored in the computer onboard the missile according to the position of the target on Earth. But the compilation of the "firing table" of the missile is far more difficult than that of an ordinary cannon. This is because in order to control the flight of the missile in the "barrel," a highly complicated control system with very specific requirements - a guidance system is needed. The guidance system, after its design and fabrication, must be tested on the ground a great number of times to ensure that its characteristics meet the design requirements. After ground tests, it must be tested in flight which means that the guidance system must be placed on the carrier of the missile to perform tests under actual conditions. During the test, a remote measuring device continuously sends the measured data of the guidance system in the missile back to the ground to facilitate the analysis of the working conditions at any time. How is the performance of a guidance system judged? This will have to rely on the accurately measured data provided by the electronic ballistics measurement system. We know that there are many factors affecting the accuracy of the missile. Among them a very important one is the position vector and velocity vector at the instant

/9

that the rocket engine is shut off. This is similar to the position and velocity of a shell at the instant of exiting from the muzzle. If the guidance system meets the requirements, then it will carry out all the prearranged "commands" accurately without any mistake which execute every move of the missile such as engine turning on and shut-off. Thus, the missile will follow the predetermined ballistics and will accurately land at the predetermined point. However, in the guidance process it is unavoidable to have some problems which means that in executing these "commands," perhaps large errors are made or some inaccuracies exist. The former may cause the missile test to fail and the latter may affect the accuracy of the landing point. In the latter case, how does one analyze which part of the system was not executing the "commands" well? To obtain this answer, we have to use the highly accurate data obtained from the electronic ballistics measurement system as the standard to compare with the data obtained from remote measurement and to compare the deviation of the landing point through analysis. The results obtained are used to further improve the accuracy of the missile and to compile an accurate "firing table." /10

With the increasing range and higher accuracy of missiles, the requirements for the guidance system are also becoming higher and higher. Correspondingly, the requirements for the electronic trajectory measurements system are also more and more stringent. For example, for a missile travelling at several kilometers per second the accuracy requirement in measuring velocity is several centimeters per second, the accuracy requirement for a measured distance of several hundred or even over 1000 kilometers is several meters. From these we find that in order to raise the accuracy of the missile, in addition to the development of carrying means and delicate design of guidance system, the requirements for the electronic ballistics measurement system are also very stringent and indispensable.

How Do Satellites Enter Orbits

On April 24, 1970, the call of our great Chairman Mao "We will also get into satellites" was realized. Our first satellite was launched into space along with the music "the East is Red."

How does a satellite enter orbit? What is its relationship with the electronic ballistics measurement system? The splendid variety show "Water Flow Star" can answer these questions. Why does the water contained in a bowl not spill out during rotation in air? Why do we have to apply more force by hand when the rotational speed becomes higher? This is because when an object is undergoing a circular motion, a centrifugal force is created. The higher the rotation speed, the larger the centrifugal force becomes. We can imagine when the string fastened to the bowl is cut during rotation then the water bowl will fly out in the tangential direction of the circular motion. If the string is not cut by a pair of scissors but instead, the string is snapped by the centrifugal force when the velocity is getting higher and higher, the bowl will also fly away similarly. Based on this reason, we can consider the gravity of Earth as an invisible string. If we want an object to rotate around the Earth, we must be able to snap this "gravity string" by some means. For an object rotating around the Earth, with increasing rotating speed, the weight is liberated from this "string" when the centrifugal force is greater than or equal to the gravitational force. It begins to rotate around the Earth and the object is a "satellite." According to calculation, when the object is rotating around the Earth at a speed greater than eight kilometers per second, it can get away from this string. Therefore, in order to make a vehicle flying around the Earth, it must have the above speed. This speed is called the first order universal speed. To accelerate the satellite to this speed, a multiple-section rocket must be used as the carrier. /11

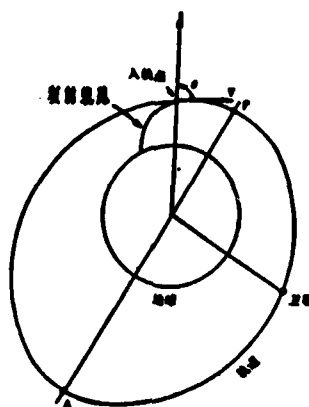


Figure 2-5.

From Figure 2-5, it can be seen that under ordinary conditions when the speed reaches the first universal speed and the direction of the velocity is parallel to that of the local horizon, the satellite can enter its orbit. The point at which the satellite enters the orbit is called the orbit centering point. Under ordinary conditions, the orbit entering point is the perigee. It is worthwhile to point out that the magnitude and direction of velocity at the orbit entering point will significantly affect the orbit of the satellite. The position and velocity of the orbit entering point are very important data determining whether the satellite can accurately enter its orbit and whether the satellite will stay in its orbit for every launch. These data will rely on the measurement of the electronic trajectory measurement system.

Multiple Targets Measurement

The preceding is a description for single target measurement. Along with the development of anti-ballistic missiles and multiple warhead separate guidance re-entry weapons, the measurement of multiple targets is on the daily agenda. When anti-

/12

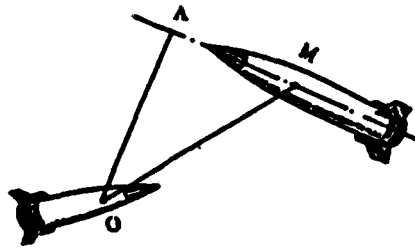


Figure 2-6. Schematic of Target Escape.

aircraft guns are used against airplanes, if the shells hit the airplane directly, there can be no better result than that. However, if the plane is shot down only when the shells hit the plane directly, then the probability of shooting down enemy aircraft is very small. Hence, usually it relies on the fragments of the shells upon explosion to hit the target. The hitting probability is then greatly increased. Therefore, for this type of shells, there is an important indicator to be given which is the power radius. Different shells have various power radii. The anti-ballistic missiles used to intercept enemy intercontinental ballistic missiles have a power radius of several kilometers. Can a newly developed anti-ballistic missile accurately intercept enemy missiles? In other words, can it fly into the power radius of the warhead? These conclusions must be determined experimentally. There are two experiments. The first is the actual firing of the real thing. It is feasible for ordinary artillery shells. If it is the case of nuclear warheads for the interception of missiles, then the situation will not allow this type of actual tests. Therefore, the second type of test, simulation test, is adopted. This method involves the firing of a simulated enemy missile and landing of the anti-ballistic missile to intercept this missile which does not carry any warhead. The purpose of the electronic ballistics measurement system is to determine the ballistics of the two targets in the encountering section. Then, based on these

data, parameters such as target escape and minimum target escape distance are calculated.

As shown in Figure 2-6, OM is the target escape and OA is the minimum target escape distance. Through these data, we can judge the characteristics of the anti-ballistic missile without actually going through the actual firing test. When intercepting an enemy ballistic missile, often times several anti-ballistic missiles are launched to intercept one missile. Hence, in the experiment, it must be capable of detecting the ballistics of several targets simultaneously. Other measurements of multiple targets are more or less similar. To accomplish this type of a mission, an electronic ballistics measurement system is undoubtedly needed. Furthermore, higher requirements are necessary.

/13

How to Retrieve Satellites

Our country not only successfully launched one satellite after another, it also successfully retrieved them to enable the astronomical industry to reach a new level. At present, there are only two countries having the "retrieval" technology. People are certainly curious about the relation between it and the electronic ballistics measurement system. In order to explain this problem, let us first talk about the simple process of satellite retrieval. As the satellite is operating normally, when it reaches a predetermined return point, the ground control issues a command to the satellite via remote control to change the angle between the satellite and the ground so that it is slightly tilted toward the ground. Then, the control rocket of the satellite is remotely ignited to reduce the speed of the satellite. After a certain period of time, the auxiliary parachute is opened and then followed by the opening of the main parachute before reaching the ground. From the above mentioned process, to reach a predetermined returning point is a key. If this position is not precise, then no accurate retrieval can be mentioned. The determination of the

position of this point still relies on the electronic ballistics measurement system. In addition, in order to predict the landing point in time, the whereabouts of the satellite must be monitored beginning from the instance that the "return" command was given. This mission must also be carried out by the electronic ballistics measurement system.

How to Ensure the Safety in the Test Area and Flight Zone

Regardless whether it is a satellite or a missile, a rocket must be used as a carrier. The rocket is far more complicated than an automobile or an airplane. When a new model is used, many ground tests must be performed. A rocket is a huge object and the fuels of a rocket engine consist of large amounts of combustible explosive materials such as alcohol and liquid oxygen. After launch, it will pass through the test area and a long flight zone with many large and small cities and important installations underneath. If there are not a pair of sharp "eyes" to monitor its whereabouts continuously, if any malfunctioning occurs, then the loss caused will be irrecoverable. This pair of indispensable "eyes" are the electronic ballistics measurement system. Then, how does the electronic ballistics measurement system carry out the monitoring work? /14

As soon as the rocket leaves the launching pad, it informs various measurement systems that "we have taken off". From this point on, the measurement system keeps a close eye on the target and the measured data are continuously sent back to the computer at the command center. On the basis of these data the computer continuously calculates the trajectory covered by the rocket and continuously compares the calculated trajectory with that based on theory. We know that the actual rocket trajectory cannot be exactly the same as the theoretical one which is normal. But the difference cannot be too great. If it is greater than a certain

degree, the computer will report to the commander that "there is a problem with the rocket". The commander then must very quickly judge whether there is a problem or not. If indeed a problem has occurred, in order to ensure the safety in the test area and its flight path, a detonation order must be given decisively. What is the appropriate time to issue such an order? It depends on the damaging effect of the fragments on the lives and property of the people. At this time, the opinion of the measurement systems must be sought in order to determine where the fragments are going to fall. If measured data show that the fragments are going to fall in deserted areas, then the detonation order can be issued. Thus, the safety of the test area is ensured and the safety of the flight zone is also protected. This heavy burden is also handled by the electronic ballistics measurement system.

The electronic ballistics measurement system, no matter whether in missile tests or in the launching and retrieval of satellites, is an indispensable piece of equipment. With the development of the astronautical industry and that of the electronic ballistic measurement system itself, its application is far more than this. The newly developed applications will be discussed later.

III BASIC CONCEPTS OF THE ELECTRONIC BALLISTICS MEASUREMENT SYSTEM RADIO WAVE, FREQUENCY AND PHASE

/15

If a pebble is tossed into calm water, then a wave will be generated. The wave propagates gradually in all directions. If we observe more closely we can find that the forward motion of the wave has some regularity as shown in Figure 3-1. The highest point is the peak and the lowest point is the valley. The distance between two peaks is a wavelength which is usually expressed as λ . The height of the peak is called the amplitude expressed by A .

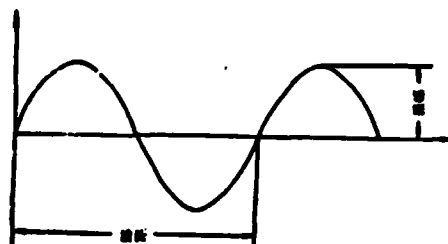


Figure 3-1. Sinusoidal wave.

Key: (1) Wavelength; (2) Amplitude.

Similarly, when we vibrate a tuning fork, the sound wave created by the tuning fork also propagates in all directions at a fixed wavelength and amplitude. Different tuning forks produce different vibrations and wavelengths. Sound waves and water waves are both mechanical waves.

In addition to the water wave which is visible to the eye and sound wave which is heard, there is an electromagnetic wave which plays an important role in one's everyday life. Visible light is an electromagnetic wave. Ultraviolet and infrared are also electromagnetic waves. Radiowave is also a kind of electromagnetic wave. The only difference is that the wavelength of the radiowave is longer than those of visible, infrared, and ultraviolet light. In addition, the radiowave, as compared with visible light, has the largest advantage that a radiowave generated by an electromagnetic oscillator has a single wavelength with good coherence. The ordinary white light produces light at various wavelengths propagating towards all directions with poor coherence. Due to the characteristics mentioned above, a radiowave is separated from the electromagnetic wave category to form an independent field.

To produce water waves we must throw pebbles onto a calm water surface and to create sound waves we must vibrate the tuning fork. These facts indicate that to make waves, work must be done.

Throwing pebbles into the water and vibrating the tuning fork are done to produce a source of oscillation. The radiowave is no exception. In order to produce a radiowave, it is also necessary to have an oscillating source. This oscillating source is the electromagnetic oscillator. This oscillator produces a current varying according to the sinusoidal curve. We all know that a varying current produces a varying magnetic field. Along with a varying magnetic field, a varying electric field is created. Thus, the cycle is repeated to form the attenuating propagation of the electric and magnetic fields centered at the oscillator which is a radiowave. Radiowaves can cross mountains and water to remote sites. The voice from Beijing is transmitted to the five continents with radiowaves

Radiowaves and visible light both belong to electromagnetic waves. Therefore, the propagation speed of a radiowave is the same as the speed of light which is approximately 300 kilometers per second. It is expressed as C. We have discussed the concept of wavelengths before. What is the relation between a wavelength and the speed of light? Their relationship is

$$\frac{\text{speed of light}}{\text{wavelength}} = \text{frequency}$$

Because each wavelength represents the length of one oscillation period, hence, frequency is the number of oscillations per second generally expressed as f which has a unit of hertz. Thus, we get the equation /17

$$f = \frac{C}{\lambda}$$

This equation clearly expresses the relation between the propagation speed of the radiowave, wavelength, and frequency which is a very basic equation.

In addition to the concepts of frequency and wavelengths of radiowaves, there is another concept which is the phase of a radiowave. For a continuous wave type of electronic ballistics measurement system, it is a very useful concept. In order to explain this problem, let us take a look at the product of electricity used daily in our lives. Household electricity is a 50 Hz alternating current. On the oscilloscope, we can see that it also varies according to a sinusoidal law. Its magnitude is related to the rotating angle of the rotor of the generator. When the rotation angle of the rotor is 0 degrees, the voltage is zero. When the rotation angle of the rotor is 90° , the voltage is the maximum. This explains that the rotor rotation angle is different corresponding to different voltages. This rotation angle is also called the phase angle of alternating current. If there are two generators with different rotor start-up positions, after generating electricity, although both are at 50 Hz frequency yet the voltages of these two generators at any moment are not the same as shown in Figure 3-2. We define this rotation angle at the initial position as the initial phase. The rotation angles corresponding to different voltages are called the phase of each corresponding point. The variation of phase angle has a 360° cycle which means that an oscillating cycle corresponds to 360° in phase angle. Based on this principle, it is possible to obtain the phase angle for each point in Figure 3-2. For example, the phase angle corresponding to point A in the figure is 90° , point B is 270° . For the lower figure, the phase angle corresponding to point A is 180° and point B is 360° . Also from the figures we find that the initial phase in the lower figure is ahead of that in the upper figure by 90° . The signal generated by an electromagnetic oscillator also has the above characteristics. For the same oscillator at different time, or a different oscillator, has a different initial phase. For two sinusoidal waves with the same frequency but different phases, it is possible to measure their phase difference. From their phase difference, it is

/18

possible to derive their time difference. If expressed by mathematical equation, then

$$\phi = 2\pi ft$$

where f is the oscillating frequency, ϕ is the phase difference between the two waves, and t is the time difference between corresponding points. This equation describes the relation between phase, time, and frequency which is a very important concept in an electronic ballistics measurement system.

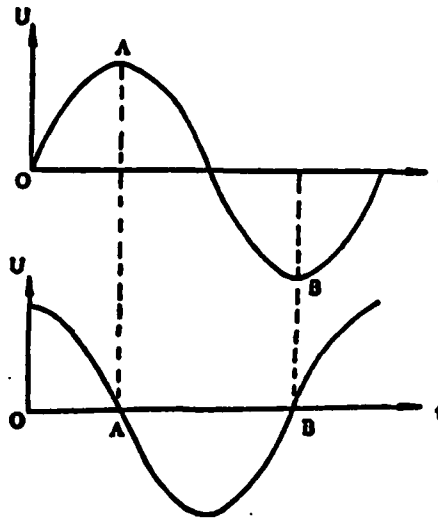


Figure 3-2. Instantaneous value when the initial phase is not the same.

Propagation of Radiowave

The radiowave transmitted by a radio station must propagate a long distance. The radiowave of an electronic ballistics measurement system also must propagate through space. They must have their own propagation means. What can happen along the propagation path? What are the effects on the radiowave under these conditions? These questions must be thoroughly understood

/19

so that the electronic ballistics measurement system can more satisfactorily accomplish its mission.

What are the characteristics of radiowaves in propagation? When we listen to the radio, we all have the experience that when the station is close then the sound is very clear and the variation in volume is not very large. But when receiving the broadcasting of a farther station, besides the volume becomes smaller, there is another unpleasant effect that the volume is always changed from high to low, back and forth. The short waveband is even more serious than the medium wave band. This phenomenon clearly indicates that during propagation in air, different frequency bands have different characteristics. Then, what are the reasons causing the above effect?

The propagation of long waves, especially ultra long waves, through air and sea water has the lowest loss. They are called surface waves. The propagation of this type of wave has good stability and low loss. Therefore, it can be steadily propagated to very far distances. However, because the frequency of this type of wave is very low, usually on the order of several tens of kilohertz, it cannot carry a lot of information. It is generally used in the transmission of air traffic control and time signals.

Medium wave relies on surface wave propagation within a range of several hundred kilometers. Therefore, within this range, the broadcasting received is very stable. With increasing distance, the decay phenomenon with the volume fluctuating begins to appear. Why does this phenomenon exist? To answer this question one must explain the approximate structure and characteristics of the ionosphere which is located from several tens to several hundreds kilometers above the surface of the Earth.

What is the ionosphere? Simply speaking, it is a space of ionized gas due to the radiation of the Sun. Ionization is the process which makes the neutral gas become charged particles - electrons and ions. Apparently, since the energy required to ionize the gas mainly comes from the energy of solar radiation, the number of charged particles in the ionosphere is related to time such as morning, noon, and night. After the Sun sets, the number of free electrons decreases significantly. With the change in the number of free electrons, the electric-gas characteristics are also varied. Among the one important factor is that the dielectric constant will also vary. The dielectric constant, on the other hand, is also related to the frequency. Hence, the ionosphere at different times has different effects on the propagation of radiowaves of various frequencies. /20

After understanding the approximate characteristics of the ionosphere, let us turn back and examine the decay phenomenon of a medium wave. This is because with increasing distance the loss of the medium waves transmitted as surface waves becomes larger. On the other hand, the part of energy of the medium wave reaching the air is reflected back to the Earth by the ionosphere. The radiowave transmitted on the ground and reflected by the ionosphere will superimpose at the receiving spot (as shown in Figure 3-3). Since the ionosphere is an unstable medium and the transmitted radiowaves are superimposed at a far distance, it is almost unavoidable to have an intermittent volume in the radio.

When shortwaves propagate, the surface waves decay very rapidly. The ionosphere is relied upon as the major means of

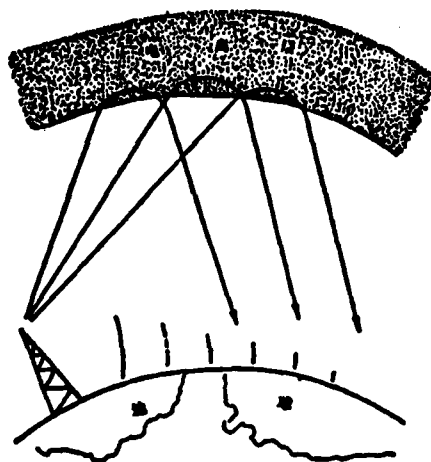


Figure 3-3. Medium wave propagation path.
Key: (1) Ionosphere; (2) Earth.

propagation. Hence, the decay phenomenon when receiving the broadcast is more serious. In addition, the characteristics of the ionosphere are closely related to day-night and season. In order to propagate radiowaves better, the frequency must be changed according to different seasons and time.

/21

When the frequency keeps on increasing and exceeds a certain value, the ionosphere no longer has a reflective characteristic. The radiowave will penetrate the ionosphere and propagate into the space. At this time, the wave propagated through the surface of the Earth has a huge loss and the ionosphere does not reflect the radiowave. Then, only direct propagation is possible. This propagation can only operate within a distance of direct vision. Television is transmitted this way. All the radiowaves in the electronic measurement system are also transmitted this way. Since the Earth is an ellipsoid, the distance of direct vision propagation is limited as shown in Figure 3-4. The direct vision distance is more or less related to the height of the antenna. If the transmitting and receiving antenna heights are h_1 and h_2 , respectively, then the direct vision distance γ_0 is
$$\gamma_0 = 3.57 (\sqrt{h_1} + \sqrt{h_2})$$

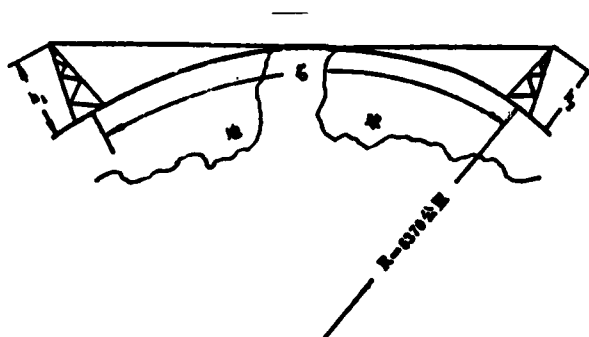


Figure 3-4. Direct vision distance in shortwave propagation.
Key: (1) Earth; (2) R-6370 kilometers.

kilometers. Therefore, a 200 meter high television antenna can only receive the television programs with a radius of several tens of kilometers.

In order to receive television programs within a wider range, it is necessary to install a high antenna. Synchronous Earth satellites are 36,000 kilometers from the Earth's surface which corresponds to the installation of a 36,000 kilometer high antenna. If there are three such satellites, then the communication and television of the entire world can be covered. This is the major reason for the rapid development of synchronous satellites in recent years. The frequencies used in an electronic ballistics measurement system are usually over several gigahertz. Its propagation is also based on the direct vision route. Therefore, the effective range of the electronic ballistics measurement system is the direct vision distance reachable under the condition that the transmitting power permits as shown in Figure 3-5.

/22

The frequency of the electronic ballistics measurement system, in addition to the consideration of the effect of wave propagation, must take many other factors into account. The main factors are:

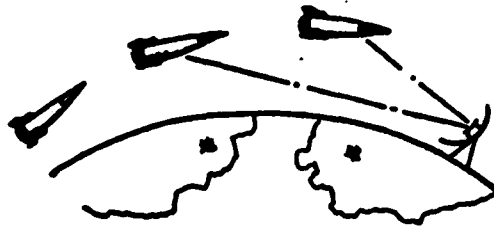


Figure 3-5. Direct vision distance of the measurement system.
Key: (1) Earth.

① prevention of interference by the same frequency. Internationally, the frequency has been divided into several bands for various applications; ② different frequency decays differently after passing through the atmosphere. The higher the frequency, the larger the decay becomes. Therefore, it is not desirable to have a higher frequency; ③ when passing through the ionosphere, different frequency will produce different refractive error (this will be discussed later). The higher the frequency, the smaller the error is. Therefore, it is desirable to have a higher frequency. The selection of frequency is a complex problem which requires the careful consideration of all the principles mentioned before obtaining a compromise.

Carrier, Wave, Signal, and Modulation

/23

In ancient times, a messenger rode on a horse to pass the information on to the next stop in order to send a message. This message can be considered as a "signal." The broadcasting stations broadcast the program using frequencies generally as low as 500 KHz. However, the frequency of the real program ranges from several tens Hz to over 10 KHz. This indicates that the broadcasted program does not directly transform various voice signals into a radiowave during transmission. This is because these signal frequencies are too low to be transmitted by the antenna and also because they occupy a wider band width. Hence, using radio-

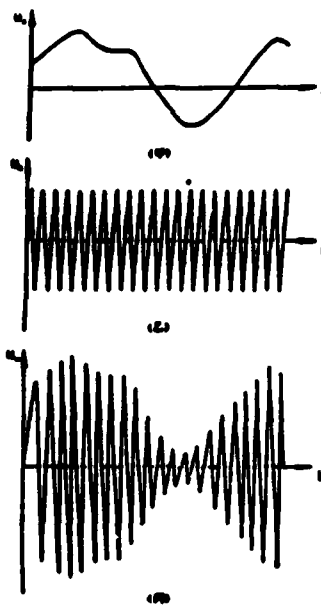


Figure 3-6. Modulating the signal.
Key: (1) I; (2) II; (3) III.

waves to transmit signals also requires a means. This means is not a horse or an automobile. It is a special tool called "carrier wave." From its name, it is the radiowave which carries radio signals. Its frequency is much higher than that of the signal.

Sending messages in the old days, the message with the messenger on the horse dashed toward the destination day and night. How do modern signals "ride" on the carrier wave? How does it transmit the signals through carrier wave to the destination? Simply speaking, this "carrier wave riding" process is modulation in radio. How is modulation realized? Let us still use the working process of a broadcasting station to explain this problem. In Figure 3-6, (II) is the carrier waves - transmitting tool. (I) is the measure or voice to be transmitted - signal; (III) is the signal already riding on the carrier wave - modulated signal. The function to complete this kind of a process is called modulation.

/24

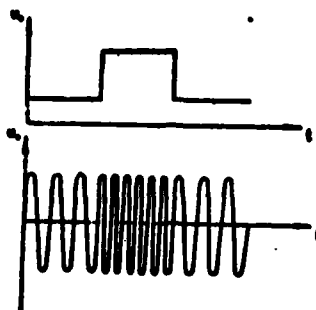


Figure 3-7. Frequency modulation signal.

The modulated signal in Figure 3-6 is that the amplitude of the carrier wave varies with varying signals. We call this type of modulation as amplitude modulation. In the modulation modes commonly used, besides amplitude modulation, there are frequency modulation and phase modulation. Frequency modulation is that the frequency of the carrier wave varies with varying signal as shown in Figure 3-7. As for the phase modulated signal, the phase of the carrier wave varies with the variation of the signal. Its wave form is similar to that of frequency modulation.

These three types of modulation have their own advantages and shortcomings. Amplitude modulation belongs to linear modulation. The amplitude of the carrier wave varies with the variation of the signal. Therefore, this type of modulation does not fully utilize its power. Its anti-interference characteristic is relatively poor. Its linearity requirement for the circuits is more stringent. In the electronic ballistics measurement system, it is not suitable to use this type of modulation. Frequency modulation belongs to non-linear modulation whose anti-interference property is better. But, for a highly accurate measurement system, its main problem is that its main oscillation frequency has relatively poor stability. Hence, the accuracy in Doppler measurement is affected. When highly accurate measurement accuracy is required, it is not suitable. Phase modulation is also non-linear modulation. It, to some extent, has the same characteristics as those for frequency modulation. Therefore, it can be

used in electronic ballistics measurement systems. Comparing phase modulation with frequency modulation, its greatest characteristic is that the main oscillating frequency is more stable. Therefore, phase modulation is widely used in highly accurate measured systems which is a better and commonly used modulation type.

Distance Measurement Signals

/25

When we are far away from a mountain and want to know the approximate distance between the mountain and us, we can shout at the mountain and after some time the reflected voice - echo can be heard. We only have to record the time period between the shouting and the hearing of the echo, we can calculate the distance using the following equation:

$$\text{distance} = \frac{\text{time} \times \text{speed of sound}}{2}$$

Mountain climbers frequently use this method to estimate their distance from the mountain.

A radiowave is very similar to soundwave, it reflects upon hitting a barrier. Can we measure the target distance if we directly emit the carrier signal? In order to explain this question, let us use an example which is frequently encountered in ordinary everyday life. In fabric stores we can see that when a sales clerk uses a stick to measure several yards of cloth he must carefully remember the number of feet. A slight error means re-measuring from the very beginning. If our stick is not a foot long, or it is longer than the number of yards of cloth we need, then the one measurement will take care of the problem. In everyday life, if we make a mistake the measurement can be repeated. But in the electronic ballistics measurement system, to measure several hundred, even several thousand kilometers, with

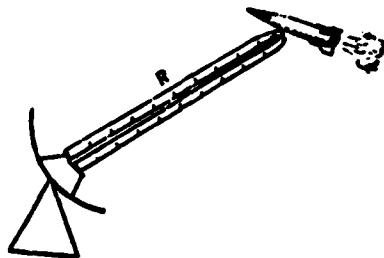


Figure 3-8. Schematic diagram of distance measurement.

a very short stick, requires numerous measurements. Nevertheless, the measurement of a target in air cannot be made with a short stick. In order to measure the distance at any moment, let us assume that there is a long stick, as shown in Figure 3-8, whose length is larger than twice the distance between the measuring station to the target. The frequency of an ordinary carrier wave is several gigahertz whose wavelength is several centimeters. This corresponds to measuring a length of several launched or 1000 kilometers using a centimeter stick. It requires measuring several thousands or even a million times. Even with a very good sales clerk, the job is too difficult to handle. The problem is more than this. In measuring the cloth, it begins with one end of the cloth and ends with cutting with a pair of scissors. However, when a carrier wave is emitted continuously, we don't know when it begins and when it ends. Even though the number of measurements can be precisely obtained, we still don't know the real distance. This phenomenon is the "fuzz effect" in measurement. Therefore, a carrier wave cannot be used to measure distance. It is necessary to modulate a distance measuring signal on the carrier wave.

/26

The usual distance measurement signals have three types:

The first type is a pulse signal as shown in Figure 3-9. In order to ensure the fuzzyless determination of the target distance,

the spacing between pulses must be greater than twice the target distance to be measured. Then, the pulse signal is modulated on the carrier wave. Thus, we do not have to worry about the situa-

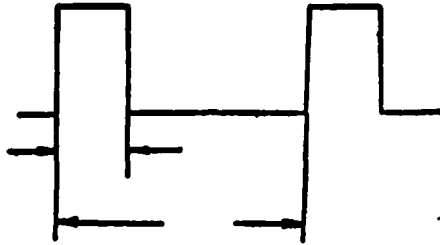


Figure 3-9. Distance measurement pulse signal.
Key: (1) Width; (2) Period.

tions mentioned before. The emitted pulse and returned pulse correspond on a one-to-one basis as shown in Figure 3-10. By measuring the time between the two signals, it is possible to calculate the distance. This signal is used in pulsed radar systems.

/27

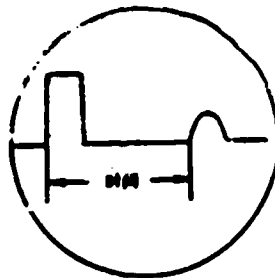


Figure 3-10. Radar return wave.
Key: (1) Time.

The second type of signal is a sinusoidal signal. A carrier wave cannot be used to measure the distance because its frequency is too high or the wavelength is too small. As a figure of speech,

this means the stick is too short. In order to lengthen this stick, we must lower the frequency or increase the wavelength. For example, when we have to measure a target 1,000 kilometers away without fuzziness, the stick must be 2,000 kilometers long. The wavelength of the sinusoidal wave must be at least 2,000 kilometers long. The frequency at this time is 150 Hz. Obviously, it is not possible to directly use the 150 Hz sinusoidal wave as the carrier wave. The 150 Hz sinusoidal wave must be modulated on a high frequency carrier wave. This kind of radar is called a continuous wave radar.

The third type of distance measuring signal is a coded signal. When we send a telegram, after writing the content, the clerk at the telegraph office writes a four digit code under each character in the content. The telegraph operator transmits the signal based on the compiled numbers. On the other side, another operator based on the series of numbers received translates the numbers back in Chinese in the form of a complete telegram to the addressee. During the process, a very important link is the transformation of Chinese characters into Arabic numbers. This is called coding. Although the code used in the telegram is expressed in decimal numbers, yet in the actual sending of the telegram there are two states. It is based on the "on" and "off" of the key and the different "on" and "off" times to represent the 10 Arabic numbers. Then, various Chinese characters are formed as a combination of these 10 Arabic numbers. The "on" and "off" state mentioned above is a binary code. The binary code is used to express a decimal code and then the decimal code is used to express the Chinese symbol. This is a complicated system. The binary system is formed by "0" and "1". It advances one digit by two. For example, the "12" in a decimal system is expressed as "1100" in a binary system. The rapid development and wide application of the binary system is used mainly because it is easy to use. For example, the "on" and "off" of a key represents all the numbers in

/28

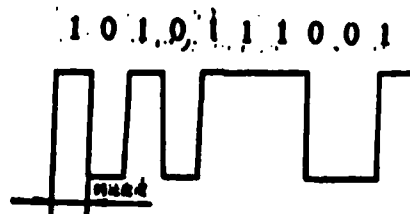


Figure 3-11. Coded pulse signal.
Key: (1) Width of an element.

a binary system. Furthermore, this "on" and "off" state can be expressed as the high, low voltage in a transistor circuit. If high voltage represents "1", then low voltage represents "0". Figure 3-11 shows a binary number and its corresponding wave form. This wave form can be called coded signals. What is the relation between this coded signal and distance measurement? A binary coded signal can be produced according to a certain law which makes the coded signal repeat itself at a needed length determined by us. For example, if the width of each pulse is called a code element width and every code element width is 100 microseconds and after 1000 pulses this series of code is repeated, then this coded signal is called a distance measuring code whose total length is obviously

$$1000 \times 100 \text{ } \mu\text{sec} = 0.1 \text{ sec}$$

In other words, this series of codes has a signal period of 0.1 sec. What does it represent in distance? It is approximately 30,000 kilometers. Hence, we can use this stick to measure a target 15,000 kilometer away without fuzziness as shown in Figure 3-12.

/29

This signal can easily solve the "fuzziness" problem in measuring distance. It has good security. Its application in measurement, especially in long distance measurement, demonstrates its high superiority more significantly. At present, planetary

voyage and synchronous orbit measurements use this type of coded signal.

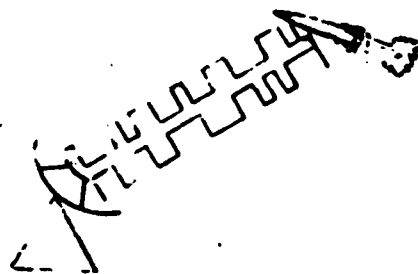


Figure 3-12. Schematic diagram of coded signal distance measurement.

Demodulation of the Signal

Why can we listen to broadcasting with a crystal receiver? This is because in the universal crystal receiver there is a key element - "crystal". This crystal has an unidirectional electrical conduction characteristic which acts as a transistor diode. This element enables the demodulation of the signal in the carrier wave and the transformation back into music or language signals (as shown in Figure 3-13). We call this process "wave detection", which can also be called demodulation to have a broader meaning. A careful examination of the process is very meaningful. In order to transmit the signals, the signals must be modulated on the carrier wave. In order to obtain the signal, it is necessary to separate the signal from the carrier wave. In a broader sense, demodulation is to separate the signal from the carrier wave, leave the signal and get rid off the carrier. The crystal wave detection in the crystal radio receiver is one of the demodulation methods.

/30

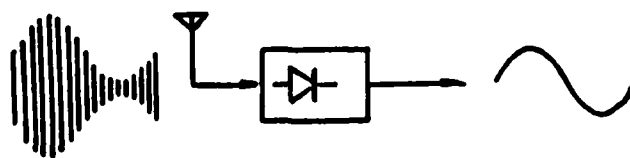


Figure 3-13.

The wave checking method discussed above has very wide applications. Radio and television picture wave detection use this method. Its biggest advantage is that it is especially simple. Can this demodulation method be used in an electronic ballistics measurement system? To explain this function, let us begin with the problems of this demodulation method. First of all, this kind of simple wave detector can only be used on amplitude modulated signals. For frequency and phase modulated signals, it is ineffective. Secondly, regardless whether it is the signals of a radio station or a television station, the signals are strong. If interference signals are added to the original signal, the receiving result becomes poorer. This is because this wave detector cannot filter any interference. Due to the two characteristics described above, this type of wave detector cannot be used in an electronic ballistics measurement system. This is because, firstly, the distance measuring signal is usually not amplitude modulated but rather frequency or phase modulated. Secondly, because the measured distance of an electronic ballistics measurement system is very far, the signal received from the antenna is very small, even the amplitude of the signal is smaller than that of the interference. In other words, the signal is buried in the noise. Under this condition, using a "crystal" type of wave detector cannot accomplish the signal receiving mission. To resolve this problem, a tremendous amount of effort has been invested into the study of demodulation technology. "Wave detectors" of various characteristics have been developed. The most commonly used are new techniques such as the matching filter, phase lock-in demodulation, and relevant receiving. Their basic working principles will be introduced later.

Geometric Principles of Determination of Position of Target in Space

On a straight line, if one wants to know the relative position between two points, it is only necessary to determine the relative distance of the two points to get the only determination. However, on a plane, if one wants to define the relative position of a point relative to a point A shown in Figure 3-14, it is not sufficient to define their relative position by measuring the distance between these two points alone, because all the points B' , B'' ---- on the circumference on a circle, centered at point A and radius R, which is the distance between points AB, satisfy the above condition. Therefore, if only the distance between point B to point A is known, one cannot define the position of point B on the plane. What should one do to define the position of point relative another point on a plane? As an example, when troops are marching, to determine the position of a place, it is necessary to know its distance from the location of the troops as well as its direction relative to the location of the troops whether it is north, or northwest, ----. If we choose the north direction as a reference axis ON, to determine the position of a point on a plane, it is only necessary to give the distance between this point and the origin of the reference axis O and the angle θ between the line linking the target M and O and the reference axis ON, to provide the only definition of the position of point M as shown in Figure 3-15. This type of expression is generally called the polar coordinate expression. Under some conditions, this type of expression is not convenient and a right angle coordinate system is used. The right angle coordinate system uses two perpendicular lines Ox and Oy to represent the x-axis and y-axis, respectively as shown in Figure 3-16. The intercept of the two straight lines

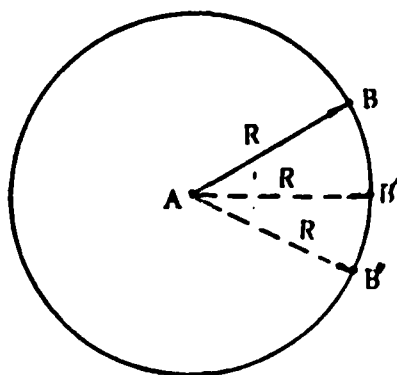


Figure 3-14.

is the origin of the coordinate system which is expressed by 0. If we want to determine the position of a certain point M relative to 0, all we have to know is the two coordinates x and y of point M to uniquely define the position of point M.

/32

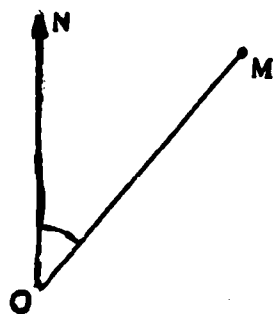


Figure 3-15. Polar coordinate.
Key: (1) North.

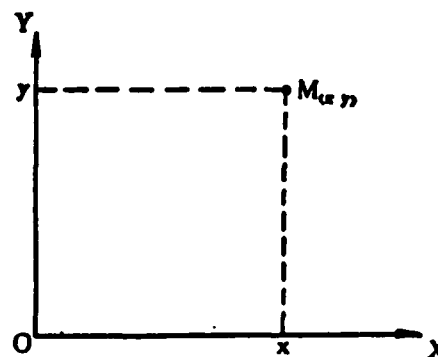


Figure 3-16. Right angle coordinate system.

For a target in the air such as a missile or a satellite, or a balloon, it is no longer a target on a plane. Under this condition, in order to define the position in space, we must find a way using solid geometry. Let us use an example to explain

this problem. The measured data of a radar usually are the distance R , the azimuth angle A and the tilt angle E_0 . How is the position in space defined through these three data points? First, we use the measuring station as the origin to form a space right angle coordinate system $O-xyz$. In this coordinate system if only the distance R is measured, then it is not possible to define the position of a target in space, similar to what happens in a plane right angle coordinate system, because any point on the hemisphere which is centered at point A with a radius R (as shown in Figure 3-17A) satisfies the condition. Similarly, /33

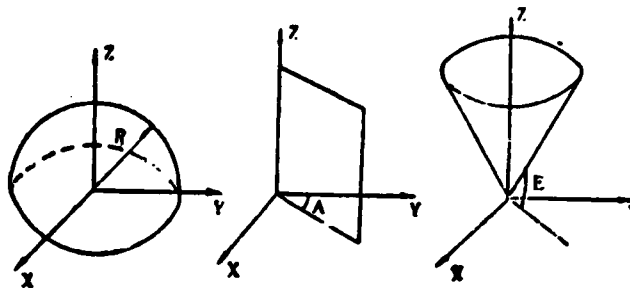


Figure 3-17. Geometric expressions of measurement elements.
(4) (A); (5) (B); (6) (C).

if only the azimuth angle is obtained, then all the points on the plane in Figure 3-17 will satisfy this condition. If only an inclination angle E is measured, then all the points on the cone in Figure 3-17 (C) satisfy this condition. Therefore, one measured data point alone cannot define the position of a target in space. However, if the three conditions can simultaneously be satisfied, which means that the three data points can be obtained simultaneously, then a unique point can be defined in space. From the point of view of geometry, a plane and a hemisphere intersect to form a curve and this curve intersects with the cone at a point as shown in Figure 3-18. This point is the position of the target in air that we want to define. On the

basis of various measurement techniques, different quantities can be determined. Different quantities in the space right angle coordinate system can form different curved surfaces. For example, in measuring the distance difference of two stations, a hyperboloid can be drawn, and in measuring the distance sum of the two stations, an ellipsoid can be plotted ----. On the basis of different quantities, various measurement elements can be determined. The R.E.A. mentioned before are all measurement elements. Different measurement elements form various measurement systems. Regardless of the measurement system, the principle of position determination is all the same. The following is an introduction of a few classical measurement systems, their measurement elements and methods.

/34

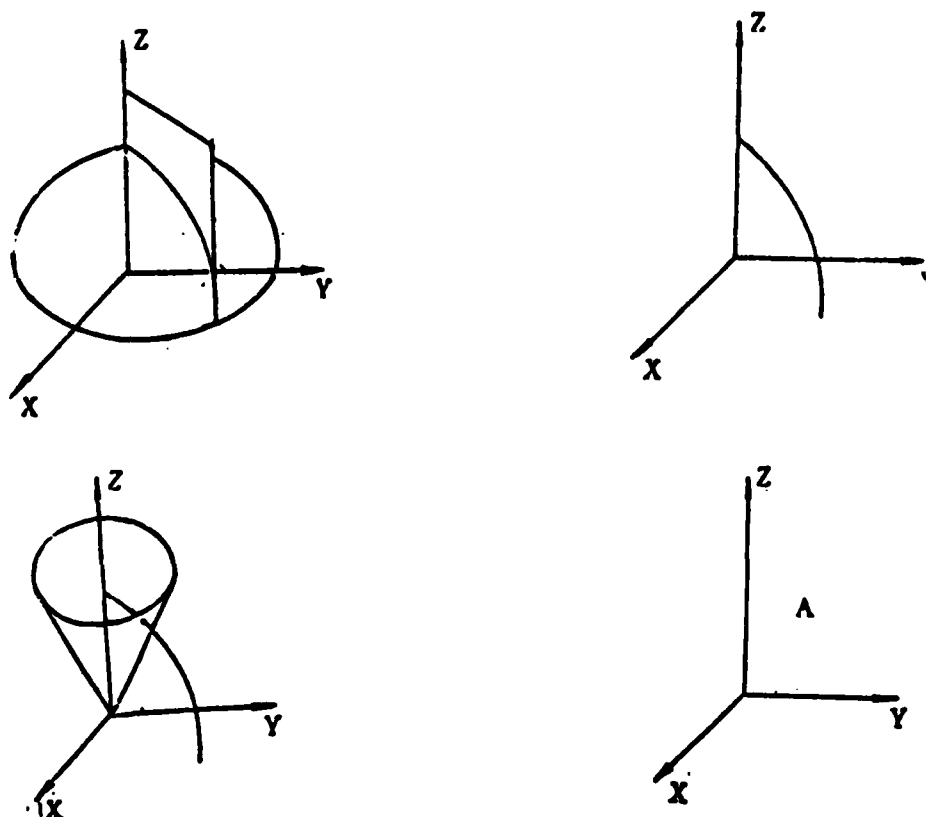


Figure 3-18. Geometric figure representation of the position determination principle;
Key: (1) (A); (2) (B); (3) (C); (4) (D).

Mathematical Expressions of the Velocity and Position of Targets in Air

In the above section, we briefly described the geometric principles of position determination of targets in space. Using this method, it is possible to more directly visualize the position determination principle. However, in the design of a practical theoretical calculation and measurement system, this space geometric concept alone is not enough. More importantly, it is necessary to clearly define the measurement elements as described above which are the mathematical relations between the quantities to be measured by the measurement system and the coordinates of the target in the measurement coordinate system. Through these relations, we can obtain the components along the coordinate axes of the position and velocity of the target in space. Because position and velocity each has three components in the three coordinate axes, in order to obtain these components, at least six equations must be established based on the measured data to solve the six unknowns. For example, the relation of the distance of the target in space R and the three coordinates can be written as

$$R = \sqrt{X^2 + Y^2 + Z^2}$$

As another example, the radial velocity and the velocity components of the coordinates can be written in the following relation:

$$V = \frac{X}{R} V_x + \frac{Y}{R} V_y + \frac{Z}{R} V_z$$

where V_x , V_y , V_z are the components of the velocity vector of the target in space on the three axes of the right angle coordinate system. According to this method, a similar equation can be written based on the quantities measured directly. From the two equations, it shows that the unknowns are X , Y , Z , V_x , V_y and V_z . For this type of equations, there must be at least six such equations to solve six unknowns. To obtain six equations, it is

necessary to measure six elements.

The mathematical method is simple and precise, which is the basic method in the design and study of measurement systems.

Basic Requirements of the Electronic Ballistics Measurement System

A complicated electronic ballistics measurement system is the monitor of guided missile ballistics, orbiting of the satellites, and the flights of aircraft. Its responsibility is so great that it does not allow any error. In addition, this type of system, from design to use, requires a tremendous amount of manpower, thousands of elements, and huge amount of money and materials. Therefore, a measuring system must be a high quality product. What are the criteria to evaluate the quality of the system?

First, it must satisfy the tactic technical objectives. Before the development of every measurement system, the users must provide their requirements based on the applications of the system. These requirements are primarily the accuracies of position and velocity measurements. They are the basis of the development of this measuring system. If the equipment cannot reach the requirements upon completion of development, then it does not accomplish any mission at all.

Second, the reliability must be high. It was discussed before that a measurement system is composed of thousands of elements. There are thousands of soldering spots and kilometers of conducting wire. If any link in the system is out of order, the entire measurement system may break down. If it breaks down during monitoring, then ever better design and higher accuracy do not have any meaning. Therefore, in a certain sense, reliability requirement is more important than accuracy in measurement. In order to quantitatively determine reliability, usually it is evaluated by the average working time period without a breakdown. To improve

the reliability, presently there are many methods in use. The most important method is the "spare". To accomplish a certain mission, two sets of equipment are used. When one set breaks down, the second set is immediately put to use. Undoubtedly the reliability can be significantly improved. However, if the entire measurement system has an extra spare system, then the equipment is too large. Thus, usually in some key parts or frequently broken down parts, the spare method is used to raise the reliability of the entire measurement system. /37

Third, it must be convenient to use. Because the electronic ballistics measurement system is very complicated equipment, the time is tight when the equipment is in use, and the work load during monitoring, adjusting, and operating is also very large; therefore, the ease of maintenance, use, and operation is also an important indicator to evaluate a measurement system. Presently, in some advanced measurement systems, concentrated operation and automatic checking of malfunctioning, etc. are adapted to enable a few people to operate such huge equipment. With the continuing development of computer technology, the degree of automation will increase to facilitate the use and maintenance of such a complicated system.

IV. BASIC COMPOSITION OF AN ELECTRONIC BALLISTICS MEASUREMENT SYSTEM /38

The Coordinative Target and the Transponder

When we use the telephone, one side is talking while the other side quietly listens. If both sides talk simultaneously, then both sides cannot understand what the other side is talking about. Therefore, only one side can talk on the telephone, which means after one side talked the other side then talks to ensure a normal telephone conversation. This working type is

called one way work. Pulsed radar works according to this one way fashion. It transmits a pulse; after the distance of a round trip, a returned pulse is shown on the oscilloscope. In order to ensure smooth operation and not to cause confusion, it is required that the spacing between the transmitted pulses must be greater than that of the round trip distance between the radar and the target. It is assured that only after the returned signal is received the next pulse signal is emitted. This is very similar to the situation of the telephone. After one side is finished talking, the other side begins to speak. However, for a continuous wave measurement system transmitting sinusoidal wave this reflective work mode has a problem. Since on one hand, the signal is continuously emitted from the antenna and on the other hand the same antenna must receive the return signal reflected from the target, the two frequencies are the same and they both appear at the antenna simultaneously; thus, the transmitted and received signal enter the receiver at the same time and it is indistinguishable between transmitted and received signals. This is similar to the telephone when both sides are talking. To solve this problem, in a continuous wave electronic ballistics measurement system, coordinative type of targets are used.

What is a coordinative target? Thus must be answered by talking about the transponder. A "transponder," by its name, is response and reply. Essentially speaking, in order to avoid the appearance of the mutual interference effect as mentioned above, one way is to separate by time, another way is to separate by frequency. Since a continuously wave signal cannot be separated by time, we have to try to separate it by frequency. A transponder is an instrument to separate frequency. After it receives the signal from the transmitter, it shifts the received frequency to make the frequency of the return signal different from that of the transmitter. Thus, it is possible to separate the continuous

/39

wave signal by frequency to meet the objective that the same antenna can transmit and receive at the same time. This working mode is called a two-way mode. Targets equipped with transponders are called coordinative targets.

After using the coordinative targets, in addition to the above effect, there is another big advantage which is the significant increase in effective range. Therefore, although interference problems do not exist with a pulse radar, yet in order to increase the effective range, transponders are also used sometimes.

Why is the effective range increased with the use of a transponder? This is because the magnitude of effective range for any radar is mainly determined by the energy of received signal by the radar. For a reflective mode pulse wave, the energy received is the energy emitted by the radar and the energy reflected back after encountering the target. When the distance is very far, this energy is very small. If a transponder is used, it is possible to transmit back to the ground at a fixed energy which is much greater when compared with the reflected energy. The effective range of the radar is then greatly increased.

Can the transponder be used then in all occasions? Obviously, a transponder can only be installed on targets in our own space. Therefore, coordinative targets can only be test targets. In addition, the signal sent back from a coordinative target can only obtain information on range and velocity and cannot reflect the characteristics of the target. When there is a need to study the characteristics of the target, coordinative targets cannot be used. Only pulse radar working in a reflective mode can be used. /40

Antenna and the Capturing and Tracking of Targets

In everyday living, a flashlight is frequently used. In order to make the light shine farther and brighter, we have to "aim"

the light. This process involves the placement of the bulb on the "focus" of the reflector. After that, a light beam is forward. In the light beam, the light intensity is especially high and outside the beam it is very dark. If the reflector and the shade are removed, the bulb will shine light in all directions. But, the intensity is relatively poor. The reflector of the flashlight corresponds to the "concentration" of the energy of the bulb in the light beam. Similarly, the energy of radiowave can also be concentrated based on this principle. The digital satellite-ground antenna designed and constructed in our country has a diameter of 15 meters which is capable of concentrating the energy emitted by the transmitter in a wave beam within a fraction of a degree. The concentration of energy can greatly improve the effective range. Presently, all the electronic ballistics trajectory systems have larger antennas to track down and measure distant targets.

Anything has two sides. Large parabolic antennas can concentrate the energy in a wavebeam in a few or a fraction of a degree to greatly increase the effective range. However, it is difficult to locate the target. For airplanes flying very high, the sound can be heard from a distance, but it is not as easy to see the airplane as to hear the plane. In order to find the airplane, both eyes must search in the sky. The vision field of human eyes - wave beam, is several tens degrees which is much wider than the fraction of a degree of the wave beam. But it is still not easy to see the airplane. The radar antenna must search several hundreds or thousands of kilometers for the target which practically corresponds to finding a needle in a haystack. Therefore, the "target capturing" problem must be resolved quickly to allow the measurement system antenna to aim at the target as soon as possible. Otherwise, measurement cannot even be made.

Our enriched life gives us many inspirations. When we look /41

up in the sky to search for a high flying airplane, in practice, the discovery of the airplane has a guiding equipment - ears. The ears hear the sound first to identify the approximate direction of the airplane to command the eyes to conduct a search in one direction so that the airplane can be seen quickly. It can be imagined, if there are no ears, the search for an airplane high up in the sky directly by eyes involves the sequential search in the sky until it is found, without using ears as the guiding equipment, despite the wide vision of the eyes. Sometimes, even before the airplane is found, it flew away long ago. This shows that the search by eyes alone is so difficult. Is it possible to install a guiding equipment like ears to allow the electronic ballistics measurement system to capture a target rapidly? The answer is yes. Modern electronic ballistics measurement system must be equipped with a guidance system. The guidance system itself is also a radar. The only difference is that its measurement accuracy is lower, the beam width is wider and the capturing of the target is quicker. After capturing the target, it quickly informs the approximate position of the target to the electronic ballistics measurement system to enable it to capture the target quickly, which is as "important" as ears.

Another method is to use a computer program to do the guiding. We all know that the launching of a missile, the orbiting of a satellite, and the lunar landing of the flight craft are motion following certain laws. We should be able to use a computer to calculate the position of a target at various time, and this position is told to the electronic ballistics measurement system to capture the target rapidly. This is similar to the situation that people, on the basis of prediction on the time at which the satellite reaches a certain place from a particular direction, prepare for the sight of the satellite. Without this type of prediction, to find a satellite on the wide sky is almost impossible. Isn't this guiding method good? Why do we still need guidance

equipment? This is because in the launching of a missile or motion of a satellite some unpredictable situations may occur. At that time, to rely on the program alone is ineffective. /42 Therefore, the two guiding methods are mutually complimentary in assuring the reliable capturing of the target. Therefore, usual electronic ballistics measurement systems use these two guiding methods simultaneously.

The antenna not only must capture the target as soon as possible, but also has to switch into automatic tracking of the target after the capture. This is because when the target is moving in space, the antenna must stay with the target from the beginning to the end so that the target is not lost. As we are observing the airplane, as soon as the airplane is in sight, we must closely stare at it. This process is to transmit the signal from the eyes to the brain, and then from the brain, to order the eyes to face the target to complete automatic tracking. The automatic tracking of an electronic ballistics measurement system is similar to that of the human eyes following the airplane. In this case, the "eyes" become the antenna and the brain becomes the complicated control circuit. The characteristics of automatic tracking is closely related to the motion of the target. In ordinary living, the airplane can always be "followed", but to "track down" a flying dragonfly is not so easy because when it flies it frequently varies the flight path and velocity. In other words, the acceleration of the target is large. In the electronic ballistics measurement system, targets with higher acceleration are more difficult to capture and track. For example, when comparing the measurement of main propulsion section and re-entry section, the capturing and tracking of target in the re-entry section is more difficult.

The Transmitter

In order to shine light on the target brightly, the flash light must have an electrical source - batteries; in order to listen to the broadcasting of a radio station, it also must have a source - the transmitter. The electronic ballistics measurement system is no exception; in order to ensure the measurement of far away targets, it also must have a source, which is the transmitter of the electronic ballistics measurement system.

The main function of the transmitter is to modulate the measurement signal on the carrier wave and then perform power amplification for the modulated signal. Finally, it transmits this high power signal from the antenna. What is the degree of power amplification? It depends on need and also on capability. A certain transmitted power can assure a certain effective range. With increasing range, the required transmitted power must increase. However, the increase in power cannot be infinite; it is mainly limited by the amplifier. For the present amplifier tube for the gigahertz range, the maximum power is several kilowatts. /43

The ordinary power amplifier tube is a speed modulation tube or a magnetic control tube. With increasing frequency, to increase the power output of the tube has a certain degree of difficulty from a technical point of view. Therefore, for a transmitter, the key problem is to develop a high frequency, high output power, high efficiency, and easy to cool high power unit. Of course, to increase the effective range, one of the methods is to raise the output power of the transmitter. However, it is not an effective way because on one hand to continue increasing the transmitted power has some degree of difficulty; on the other hand, the increase in power does not bring significant improvement in the effective range. The most effective method is to use new detecting techniques to improve the sensitivity of the receiver. The composition of the transmitter is shown in Figure 4-1. /44

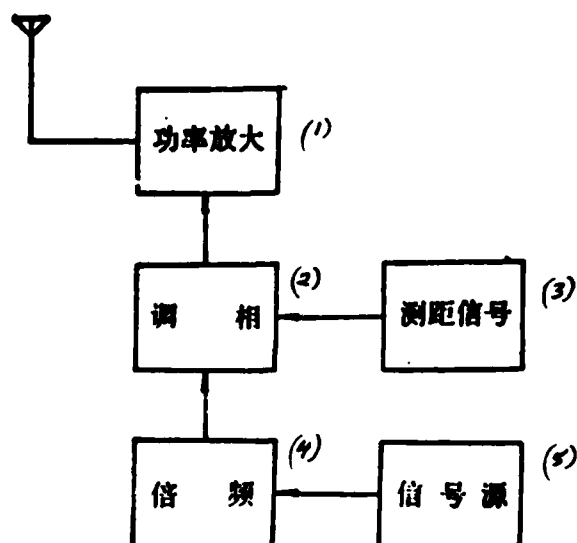


Figure 4-1. Schematic diagram of the composition of a transmitter.
Key: (1) Power amplification; (2) Phase modulation; (3) Distance measuring signal; (4) Frequency multiplier; (5) Signal source.

The Receiver

It was mentioned above that the effective way to raise the effective range is to improve the sensitivity of the receiver. How can the sensitivity of the receiver be improved?

In stormy weather, when we turn on the radio it is very difficult to listen to a broadcast clearly. This is because the thunder and lightning produce a very strong interference signal to reach the radio receiver together with the signal of the radio station. The signal needed is then "buried". In addition to the kind of intense and occasional interference such as thunder and lightning, another type of noise is always around which is the "thermal noise". This kind of noise has very little effect on listening to the radio. Usually, it is not considered.

"Thermal noise" by its name is the noise caused by heat. As

we know, only at absolute zero the electrons stop moving around. At ordinary temperature, the electrons always move randomly. In the receiver circuit, this kind of motion causes the thermal noise.

The power of thermal noise is affected by many factors. In the electronic ballistics measurement system, the noise power per unit frequency band is used to judge the magnitude of the noise. Generally, it is around 10^{-20} watts, which is very small. In ordinary radio, it is not even considered. However, in the electronic ballistics measurement system, the signal received is very weak, usually around 10^{-12} - 10^{-16} watt. For this kind of weak signal, it is necessary to take the effect of thermal noise into account. The signal transmitted from the transponder to the ground together with this noise signal are superimposed to form a new mixed signal. In general, the signal is "drowned" in the noise. The function of the receiver is to find the real signal from this type of mixed signal and to filter the useless noise to the degree possible. Obviously, to extract the useful signal from a signal buried by noise can not be completed using a simple radio receiver. A new method must be found to solve this problem. The most frequently used method at the present time is the relevance receiving method. /45

Speaking about relevance receiving, we have to begin with the characteristics of noise. Noise is a orderless random interference signal. The wave form, amplitude, and frequency from moment to moment are completely unrelated. It is not possible to predict its amplitude and characteristics at the next moment, based on the amplitude and frequency at the present time. However, periodical signal is completely different. The signals between now and then have rigorous relevance. In order to indicate this relevance characteristic, usually it is expressed by a relevance function. The relevance functions between noise and noise, noise and signal, and signal and signal can be obtained respectively.

For example, the noise relevance function at different times is zero and the relevance function between signal and noise is also zero. The basic principle of relevance receiving is based on using different relevance functions at different times for different signals to distinguish signal from noise. The equipment which is capable of completing this process is called a relator, as shown in Figure 4-2. From that figure, the simple demodulation process can be understood. The new mixed signal which is a mixture of signal and noise is sent to the input of the instrument. In the meantime, a locally generated signal is also put into the instrument after a time delay, which corresponds to the time of distance measurement. Then, the two signals are related on the instrument. When a signal is related to a signal, a signal output is obtained. When a signal is relating to noise, the relevance function is zero. Thus, it is possible to extract the signal drowned in noise. To complete this type of mission, there are several methods. For example, the matching filter in pulse radar, the phase lock in receiver on the electronic ballistics measurement system, and the relator in coded distance measurement are a few of them. /46

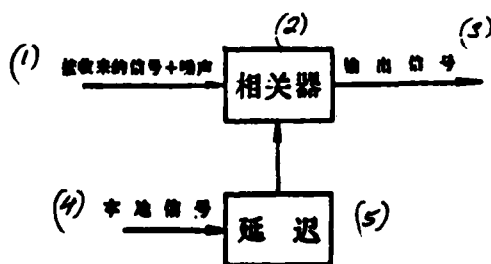


Figure 4-2. Principle of relevance demodulation.

Key: (1) Received signal + noise; (2) Relator; (3) Output signal; (4) Local signal; (5) Delay.

The principle of this type of receiver can be explained using a not too rigorous example. Two secret agents never met before

must make contact. They then must have a special arrangement to connect their relations, such as passwords or signals, etc. to allow them to accurately make contact among large numbers of people. If we consider other people as the "noise" then the person to contact is the signal and the code is the "relator".

Of course, the receiver is not a relator alone. It is similar to an ordinary differential receiver. Same as a television receiver, it consists of a high frequency head, frequency mixer, middle frequency amplifier, etc. Figure 4-3 is the block diagram of the composition of a receiver.

For a high quality receiver, the sensitivity must be high. This means that under a fixed noise level, the power of signal distinguishable is small. Presently, it can reach 10^{-14} - 10^{-16} watt. The high frequency amplifier itself must have a small noise coefficient. For a receiver measuring the phase, it is required to have a small phase error and the receiver must be reliable. After using relevance receiving, for phase modulated signals, it is possible to extract useful signal from a mixed signal whose signal power is much less than that of the noise. /47

The Terminal

Without a speaker, we cannot hear voices from a radio even with the best equipment. Without the imaging tube, a television set is no longer a television set. The speaker of a radio and the tube of a television are their terminal equipment. Similarly, a complete electronic ballistics measurement system must have its terminal facility. However, it does not require sound or a picture, but it needs measured data. The function of the receiver was introduced earlier. Its main function is to extract distance measuring and velocity measuring signals. However, the distance and velocity are not known. At this time, it must rely on the

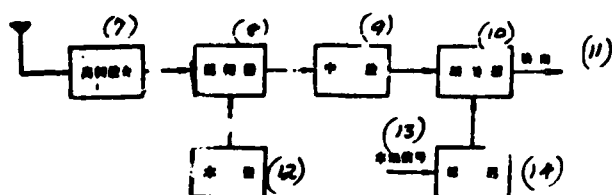


Figure 4-3.

Key: (7) High frequency amplifier; (8) Frequency mixer; (9) Medium frequency amplifier; (10) Relator; (11) Output; (12) (13) Local signal; (14) Delay.

terminal to treat and process the signals detected by the receiver to obtain the needed data.

How does the terminal treat and process the signals sent from the receiver? Let us use distance measurement as an example to explain the working process of the terminal. As shown in Figure 4-4, the signals from the receiver and the reference signal are sent to the terminal simultaneously. The distance measuring terminal is a phase analyzer and some coding, decoding, and pulse control instruments. This means that the measured phase value is transformed into binary coded signals to be placed in a temporary memory. These data are then taken out of the temporary memory according to a unified control signal for the system at a specific time to the computer or magnetic tape recording device.

/48

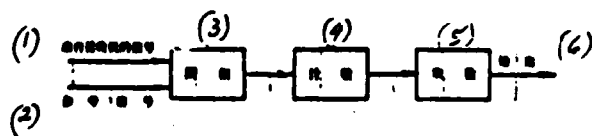


Figure 4-4. Schematic diagram of distance measuring terminal.
Key: (1) Signal from the receiver; (2) Reference signal; (3) Phase measurement; (4) Counting; (5) Extracting; (6) Output.

The terminal is basically formed by switching circuits. Hence, with the appearance of integrated circuits, especially large scale integrated circuits, the terminal rapidly moves to miniaturization and solid-state. Recently, microprocessors have been used. It will change the role of the terminal more significantly. The function of the terminal is going to be strengthened and generalized. Along with the operation of microprocessors, a great revolution has occurred to terminals and receivers without any doubt. The relevance receiving technique discussed before, essentially, is the treatment and processing of signals. Hence, it is entirely possible to consolidate this portion with the terminal and replace it by a microprocessor. This is not merely an idea; it has already been realized.

An electronic ballistics measurement, except the major parts described above, must have a power supply system to provide energy needed to each part. The unified timing duty system is also indispensable. It provides the various time standards, frequency standards, and various signal sources for the entire measurement system.

Tracking and Processing of Data

The present measurement system is not a two station unit but includes multiple measurement stations to accomplish the job. For example, in the observations of satellite in orbit and manned spacecraft, many stations are mobilized to accomplish the mission of measurement. The data obtained from each station must be centrally processed. Therefore, these data must be transferred to a data center. Some of the data must be sent over several hundred or even over 1000 kilometers away. How to transfer these data to the data processing center without error is also an important subject. For example, the measured result is 1,200 kilometers and the terminal transforms into a binary code, and this code is transferred to the data processing center through transmission equipment

/49

and circuit. If due to external interference or due to problems of the transmission equipment and circuit, the transmitted code has a mistake such that the code received by the data processing center represents a distance of 1600 kilometers or other number instead of the 1200 kilometers, then the measured results which cost tremendous effort are wasted. Hence, this type of error is absolutely prohibited. In order to solve this problem, very stringent requirements are imposed on the transmission equipment and circuits. Of course, it is ideal to have no mistake at all. However, in practice, absolutely no mistake is impossible. Then, it is necessary to specify the magnitude of the error. This is a very important indicator of transmission equipment and circuit - error code rate. For this indicator, the actual need is on one hand, while the feasibility is on the other. In order to meet the requirements, it is necessary to transfer the same data via several routes simultaneously to improve this error code rate indicator.

No matter how small the error code rate is reduced to, there is a finite probability of error. What to do then? This requires carrying out data processing before computing ballistic parameters. The scope of data processing is very wide, which is already far outside the scope of this book. However, we can briefly examine its function. For example, if an error occurs in the transmission so that 1200 kilometers is transferred as 1600 kilometers or other numbers. One of the functions of data processing is to judge which errors are caused by measurements and which are caused by data abnormality. After discovery of the 1600 kilometer data and judging that it is not a normal error, this number should be deleted from the data. Then, from the data before and after the point, a more reasonable number is filled in. This process is called data rationality examination. Commonly speaking, it is the checking of data. The qualified stays while the unqualified is rejected. What is qualified and what is not

/50

qualified must be determined based on a mathematical method according to the actual situation. Data processing must also complete the processing of error due to noise to minimize it. This is called the smoothing of data. With the development of electronic ballistics measurement systems, data processing and data processing methods are also continuously developed and perfected.

Composition Scheme and Working Procedures

The schematic diagram of the composition principle of the electronic ballistics measurement system is the following:

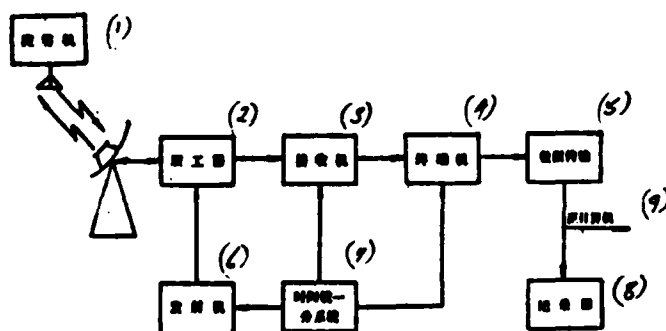


Figure 4-5. Schematic diagram of composition.

Key: (1) Transponder; (2) Two-way machine; (3) Receiver; (4) Terminal; (5) Data transfer; (6) Transmitter; (7) Time synchronizing subsystem; (8) Recorder; (9) To computer.

When the measurement of a target is about to start, guidance data of the guidance program or other guidance equipment are sent to the measuring antenna to allow it to capture the target rapidly. After the target is captured, the antenna is switched to the automatic tracking working condition and then the actual measurement begins. The transmitter sends the modulated measurement

signal to the antenna and then it is emitted to reach the transponder. The two-way machine has a separation effect. It separates the transmitted and received signals so that they don't interfere with each other. After receiving the signal, the transponder changes the frequency of the carrier and retransmits it back to the ground. The ground stations through the same antenna use a receiver to extract signals buried in the noise. These signals are distance measuring signals and carrier wave signals. The former is sent to the distance measuring terminal to calculate the distance data, and the latter is sent to the velocity measuring terminal to calculate velocity data. These data on one hand, through data transmission equipment and circuits, reach the data processing center to provide data for the safety assurance of the test area and flight path. On the other hand, they are recorded on magnetic tape for the further analysis and processing of data after the test, in order to determine the accuracy of the missile and other analyses. / 51

V THE DOPPLER VELOCITY MEASUREMENT AND POSITION DETERMINATION SYSTEM

When we ride on a train we can feel that the whistle of the oncoming train is especially ear-piercing. If we carefully recall, the ear-piercing pitch is varying. Initially, the pitch is very sharp; but after we pass by, the tune is no longer that "sharp." This phenomenon is the Doppler effect. This is because in 1842 Doppler first discovered this effect; therefore, people call it the Doppler effect.

The change in tune discussed above is actually the variation of the frequency of the whistle. Why does this phenomenon occur? If we have a fixed tuning fork, after vibration to produce a sound, if the vibration frequency of the tuning fork is f_B and the sound propagation velocity is C , then the wavelength λ_B of the vibration as discussed in Section III has the following

relation

$$f_B = \frac{C}{\lambda_B} \quad (5-1)$$

For a standard tuning fork, f_B is a constant and the velocity of sound propagation is also a constant; therefore, λ_B must be a constant. Under this condition, we hear a sound with a fixed tune. If the tuning fork has a relative motion to us with a velocity V_B , then the relative sound propagation speed of the tuning fork vibration has an additional velocity V_B on top of the base propagation velocity. Based on the principle of velocity addition, the sound propagation speed becomes $C + V_B$. At this time the tuning fork vibrational frequency f_p that we hear is equal to

/53

$$f_p = \frac{C + V_B}{\lambda_B} = \frac{C}{\lambda_B} + \frac{V_B}{\lambda_B} \quad (5-2)$$

Comparing f_p with f_B , we can find that f_p has an additional term which is V_B/λ_B . This term is due to the relative motion between the tuning fork and us. We call this term the Doppler frequency and denote it as f_d . Therefore

$$f_d = \frac{V_B}{\lambda_B} \quad (5-3)$$

What problem can we see from the above equation? That is when the frequency of the tuning fork is fixed, λ_B is a constant and is very easy to find from the frequency. This indicates that the magnitude of the Doppler frequency is proportional to the velocity relative to the observer. When λ_B is known, it is possible to directly find the velocity V_B from the magnitude of the Doppler frequency. This equation is the mathematical expression of the Doppler effect which is also the basic equation of the Doppler measurement system.

How to Measure Velocity

How is the velocity measured? This question may appear to be weird. Didn't we talk about the fact that the relative velocity is proportional to the Doppler frequency? The answer is affirmative. But how do we measure the Doppler frequency? How do we realize this measurement with the actual equipment. These are the problems we would like to discuss.

We can imagine that the tuning fork vibrator is replaced by an electromagnetic oscillator and it is installed on a rocket. At this time, there is a relative motion between the electromagnetic oscillator and the measuring station. If the frequency of the oscillator is a constant, the frequency received on the ground is no longer the original frequency. There is an added Doppler frequency. How large is this frequency? It must be compared with the frequency of the electromagnetic oscillator installed on the rocket. Roughly speaking, this is easy to realize, because before the rocket is launched the frequency of the electromagnetic oscillator can be measured. Then, it is compared with the frequency measured on earth and the difference is the Doppler frequency. In principle, it is feasible, but in practice, it is not. Why? Presently, the requirements of velocity measurements for missiles, satellites, and spacecraft are very high. In order to accurately measure velocity, we must accurately measure frequency. This requires that the oscillating frequency of the electromagnetic oscillator be stable and precise. If the oscillator itself has a relatively large frequency variation then it is impossible to accurately measure the frequency. However, it is difficult to install a stable and accurate electromagnetic oscillator on a rocket due to the limitations by volume, weight, and working conditions. In order to resolve this problem, usually a two way Doppler system is used. Its working principle is shown schematically in Figure 5-1. /54

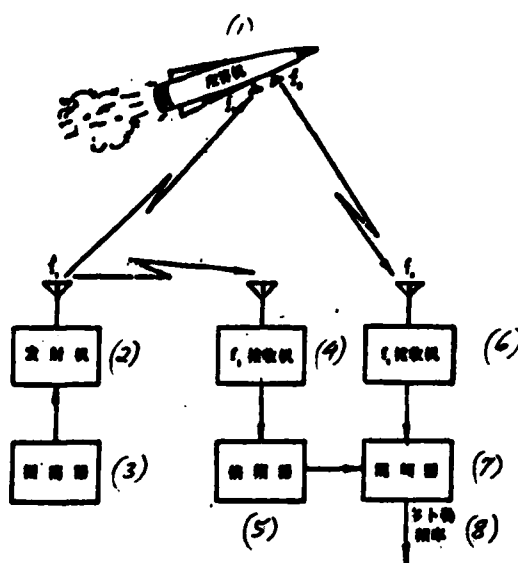


Figure 5-1. Schematic diagram of working principle of Doppler measurement system.

Key: (1) Transponder; (2) Transmitter; (3) Oscillator; (4) f_1 receiver; (5) frequency estimator; (6) f_1 receiver; (7) accurate frequency analyzer; (8) Doppler frequency.

In this system, in order to solve the problem of the standard frequency used in the comparison, the electromagnetic oscillator is not located on the rocket but is in the ground station. Let us assume the frequency of the electromagnetic oscillation generated on the ground is f_1 . This signal is amplified by the transmitter and then transmitted through the antenna toward the target in space. On the target in space, a transponder is equipped whose function is to shift the frequency of the received signal to another frequency. The ratio of the frequencies received and re-transmitted is defined as the re-transmission ratio of the transponder. When the rocket receives the signals from the ground, due to Doppler effect, the received signal is f_2 instead of f_1 . The difference between f_2 and f_1 is the Doppler frequency created by the signal from down to up. If the frequency re-transmission ratio of the transponder is a fixed constant n ,

then the frequency transmitted by the rocket toward the earth f_3 is

$$f_3 = n f_1 = n f_1 \left(1 + \frac{V}{c}\right) \quad (5-3)$$

The frequency received on the ground is that with another Doppler frequency which becomes f_4 and

$$f_4 = f_3 \left(1 + \frac{V}{c}\right) \quad (5-4)$$

The frequency directly transmitted from the transmitter to the receiving station on the ground is still f_1 because they are both fixed on the ground without relative motion and, therefore, without any frequency change. f_1 can be multiplied by the re-transmission ratio n . This number is then subtracted from f_4 to obtain f_5

$$f_5 = f_4 - n f_1 \quad (5-5)$$

If we substitute (5-3) into (5-4) and then substitute (5-4) into (5-5), we can get the relation between f_5 and the velocity V , i.e.,

$$f_5 = \frac{n f_1}{c} \left(2V + \frac{V^2}{c}\right) \quad (5-6) \quad /56$$

In equation (5-6), V is the relative velocity of the rocket with respect to the measurement system, c is the speed of light, which is usually 300,000 kilometers per second, as is the known re-transmission ratio, and f_1 is the frequency of the electromagnetic oscillator on the ground. The second term in the parenthesis in equation (5-6) can be neglected because the relative velocity of the rocket with respect to the measurement system is a very small number as compared with the speed of light. Thus, equation (5-6) can be simplified as

$$f_s = \frac{2\pi f_1}{\lambda} V \quad (5-7)$$

Therefore

$$V = \frac{c f_s}{2\pi f_1} \quad (5-8)$$

From equation (5-8) we can see that on the right side of the equation as long as f_s is known, it is possible to obtain the velocity V . f_s is the frequency measured at a station on earth; thus, the mission to measure V is accomplished.

As we know, velocity is a vector. In other words, to describe this entity, not only the magnitude must be known, but also its direction must be available. Previously, we mentioned that through the measurement of the Doppler frequency f_s the velocity V can be obtained. However, only the magnitude of the relative velocity of the rocket with respect to the ground measurement system is known and its direction is not known. In order to obtain its direction, there must be at least three such measuring stations as shown in Figure 5-2 to form a complete Doppler measurement system.

How to Determine Position

The use of a Doppler measurement system to define a position is more complicated than using it to measure velocity. From the introduction before, because the measured Doppler frequency is proportional to the velocity, knowing the Doppler frequency means knowing the velocity. How do we use the Doppler frequency data to define position? In order to explain this problem, we should start with the Doppler frequency distance measurement of a single station.

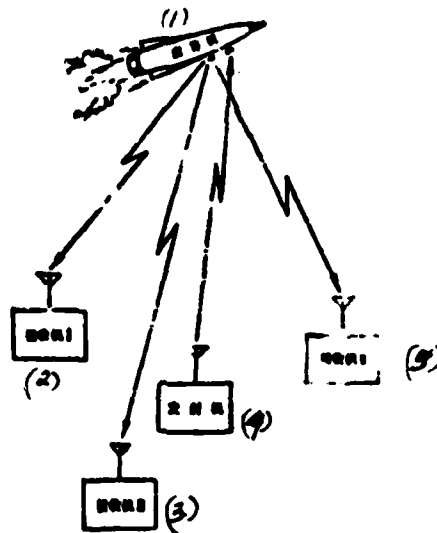


Figure 5-2. Schematic diagram of the formation of a Doppler measurement system.

Key: (1) Transponder; (2) Receiver I; (3) Receiver III, (4) Transmitter; (5) Receiver II.

In the selection on the Doppler effect, the principle behind which Doppler effect is based on has been discussed. When the side transmitting the signal is relatively still with the side receiving the signal, the signal transmission velocity is the speed of light. At this time, there is a fixed relation between wavelength, frequency and light speed. When there is relative motion between the two, the signal transmission speed is changed. It is equal to the sum of light speed and the relative motion speed. The frequency and wavelength of the transmitted signal are not changed; only the frequency of the receiving end is changed. If the velocity of the relative motion is a fixed constant, then the Doppler frequency is also a constant. If the target moves at this invariant speed, after a time period T , apparently, the distance that the target travelled is $T \cdot V_0$. For uni-directional Doppler frequency there is

Hence
$$f_d = \frac{V_0}{\lambda_0}$$

$$S = T \cdot V_0 = T \cdot f_d \cdot \lambda_0$$

where S represents the distance covered in time T . What is the meaning of the term $T \cdot f_d$ on the right hand side of the equation? It represents the cumulative Doppler cycles in time T . It can also be found from this equation that f_d is the number of cycles in a unit of time, which is frequency. f_d multiplied by the time period T represents the number of cycles in T seconds. λ_B is the wavelength of the oscillating signal of the electromagnetic oscillator with unit in meters. Then, the final division is a length unit. Hence, as long as the number of Doppler cycles in a period of time is known, it is possible to determine the distance travelled within this period of time. The distance measurement of a Doppler measurement system is handled this way. From the above introduction it is also possible to find that relying on the total number of cycles of Doppler frequency measurement in a period of time can only determine the relative distance in this period of time. It cannot obtain the total distance of the target relative to the launching point. Therefore, in a Doppler measurement system, in order to determine the total distance, we must give the initial position of the target when the measurement begins. With this initial value, we can measure the distance of the target, In measuring velocity, in order to determine the velocity vector, at least three stations must be set up. Through these three stations, it is possible to calculate the distances of the target from the three stations. With three distances, it corresponds to drawing three hemispheres in space. The intersect of these three hemispheres can be used to determine the position of the target. Therefore, a Doppler measurement system not only measures the velocity but also defines the position. Hence, this system is called the Doppler velocity measurement position determination system. /59

The most significant characteristic of the system is that the accuracy in velocity measurement is very high. This is not reachable by any pulse radar. Another advantage is it is simple and reliable. Hence, although this measurement system emerged since

the late 1940's, it still maintains a lot of life. Furthermore, on the basis of this system, a more perfect new system is developed.

There are also shortcomings for this system. It does not have the capability to directly measure distance. It relies on the accumulation of Doppler cycles to calculate the distance with the provided initial position. Therefore, the accuracy in position determination is poorer. In order to overcome this point, a new system has been developed which is the one going to be introduced later.

VI THE PHASE COMPARISON MEASUREMENT SYSTEM

/60

Principle of Angle Measurement Using Phase Comparison

The measurement system mentioned before does not have a way to directly measure position. Therefore, there is a certain degree of limitation in application. The measurement system with a position measurement method is the phase comparison measurement system; the nucleus of the principle of this system is phase comparison angle measurement.

On a straight line, let us place two antennas A and B. Their distance is D. In space there is a target S which may be a missile, a satellite, or a spacecraft. The target continually transmits a radiowave to the ground as shown in Figure 6-1. The distance from S to antenna A, from S to antenna B, and from S to the middle point of AB is R. Based on the cosine theory, we can write the following equations:

$$a^2 = \left(\frac{D}{2}\right)^2 + R^2 - D \cdot R \cdot \cos\theta \quad (6-1)$$

$$b^2 = \left(\frac{D}{2}\right)^2 + R^2 + D \cdot R \cdot \cos\theta \quad (6-2)$$

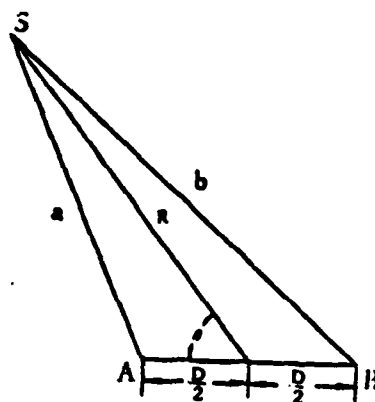


Figure 6-1. Principle of phase comparison angle measurement.

Subtracting (6-1) from (6-2) we get

/61

$$b^2 - a^2 = 2R \cdot D \cdot \cos \theta \quad (6-3)$$

(6-3) can be rewritten according to theory as

$$(b + a)(b - a) = 2R \cdot D \cdot \cos \theta \quad (6-4)$$

Hence

$$(b - a) = \frac{2R}{b + a} D \cdot \cos \theta \quad (6-5)$$

Under normal condition, D is only several tens of meters and R is several tens of kilometers or even several hundreds or thousands of kilometers; therefore, it can be approximated as

$$a + b = 2R \quad (6-6)$$

Substituting expression (6-6) into (6-5) we obtain

$$b - a = D \cdot \cos \theta \quad (6-7)$$

The angle θ in the above equation, as shown in Figure 6-1, is the angle between the line connecting the middle point of the two antennas and the target and the line AB. This is the angle which we have to measure. Because this angle is known, then as des-

cribed in Section III, the target can be defined on a cone with a cone angle θ . If three such cones are obtained, then the position of the target in space can be determined. How is the angle θ measured? In equation (6-7) we can see that D is measured ahead of time and the key is to determine $b-a$. From Figure 6-1, we find that $(b-a)$ is the difference in distance between the target in space to antenna A and antenna B. Therefore, if the difference in distance from the target to antennas A and B is determined, the angle θ can be found. There are two ways to measure a difference in distance. One is to separately measure the distance from S to A and from S to B and then subtract one from the other. The other method is to install an electromagnetic oscillator on the target in space. The oscillator continuously transmits radiowaves to the ground. Because a is not equal b , hence, the phase of the radiowave transmitted from the same point source is different at antenna A from at antenna B. The phase difference of the received signal by the two antennas is approximately proportional to $(a-b)$. If expressed by an equation, it is

/62

$$a-b = \frac{\lambda}{2\pi} \phi$$

where λ is the wavelength of the radiowave, π is a constant, and ϕ is the phase difference of the signals received by the two antennas A and B which can be measured based on the principle shown in Figure 6-2.

Once the magnitude of $a-b$ is known, the angle θ can be obtained using the following equation:

$$\cos \theta = \frac{a-b}{D} = \frac{\lambda \phi}{2\pi D}$$

where $\cos \theta$ is the cosine of the angle θ . This method to measure the angle θ (or more precisely to measure $\cos \theta$) is called the phase comparison angle measurement method.

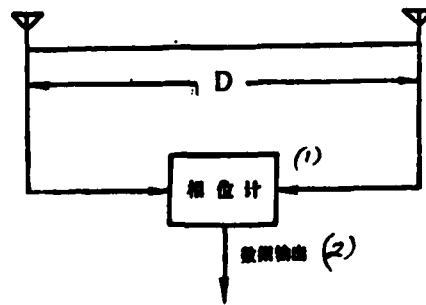


Figure 6-2. Schematic diagram of the principle of phase difference measurement.

Key: (1) Phase analyzer; (2) Data output.

How to Define Position

From the above description, we know that with a pair of antennas we can determine the angle between the target and the mid point of the two antenna. The line between these two antennas is called the base line. If only a pair of antennas exist, then there is only one measured data point. At this time, the target can only be deformed on a cone which uses the base line as the axis, the midpoint of this baseline as the vertex, the lines between the vertex and the target as the formation lines, and the vertex angle θ as the core angles, as shown in Figure 6-3. If another

/63

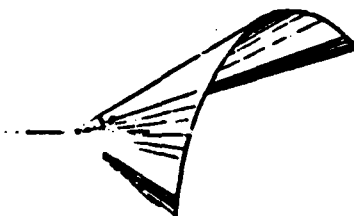


Figure 6-3. Geometric expression of angle measurement.

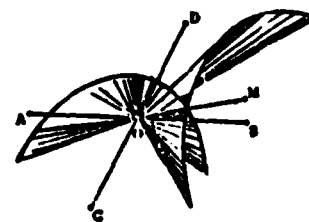


Figure 6-4. Intersect of two cones.

baseline is placed in the perpendicular direction with respect to the original base line, similarly the angle between the target

and the middle point of that baseline and the baseline itself can be measured. Another cone can be drawn which intersects with the original cone to form a line connecting the vertex of the cone to the target. The target is then on the straight line, as shown in Figure 6-4, because this line is not only on the cone using the AB base line as the axis, but also on the cone using CD as the axis. Apparently, to determine the position of a target in space, it is only necessary to determine one more parameter. This parameter can be the distance, or the direction cosine measured from a third base line. If the distance between the vertex of the cone to the target R is measured, then a sphere using the vertex as the center and R as the radius will intersect with the straight line to determine the position of the target in space. In actual practice, it is very difficult to determine the intercept using a geometric method which is also unnecessary. Usually, the three measured parameters and the relevant mathematical equations are written and the solution is sought mathematically. For example, in a right angle coordinate system as shown in Figure 6-5, let the two base lines be the X and Y axis. The origin of the coordinate is the intersection of the two base lines. Let us assume that the position of the target in this coordinate system is X, Y and Z. The direction cosine of a base line in the X-direction l and the direction cosine of the baseline in the Y direction m are measured. In addition, the distance from the original to the target is know. Then, the following equations are obtained:

$$\begin{aligned} X &= R \cdot \cos \beta = Rl \\ Y &= R \cdot \cos \alpha = R \cdot m \\ Z &= R \cdot n \\ n &= \sqrt{1 - l^2 - m^2} \end{aligned}$$

From these three equations , the position of the target in space in the rectangular coordinate system can be determined. Of course, there are other methods, such as radar and Doppler velocity

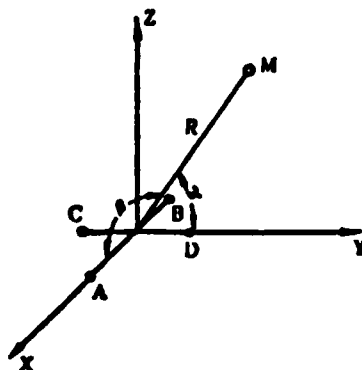


Figure 6-5. Principle of position determination.

measurement and position determination systems as introduced before, to determine position in space. The following is an introduction of another system.

How to Measure Velocity

The measurement of velocity of a target in space can be considered the measurement of Doppler frequency. Based on the actual system, different methods can be used. In the phase comparison measurement, to determine the position we have to measure the phase difference between the two antennas on a base line. What about measuring velocity? We can still use this unique characteristic to measure the Doppler frequency difference between the signals received by the two antennas on the same base line as shown in Figure 6-6. Why do the received Doppler frequency differ from the two antennas on the same base line? Because in order to increase the accuracy of velocity measurement, the usual base line length for measuring velocity is much longer than that of a position determination base line. Hence, the relative velocity between the target and the two antennas is not equal. The longer the distance, the larger the difference becomes. The Doppler frequencies received by them are not the same. More intuitively speaking, the larger the difference between the two numbers, the easier it is to measure it. Therefore, the base-

/65

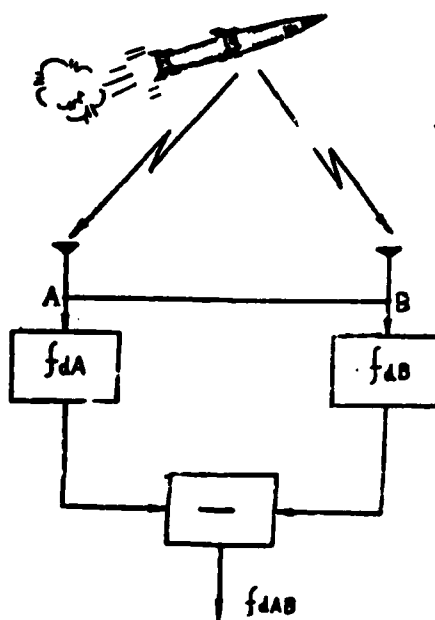


Figure 6-6. Principle of Doppler frequency difference measurement.

line should be longer. It usually ranges from several hundred meters to several kilometers. Similar to the situation in determining the position, it is possible to determine the relative velocity of the target in space with respect to the measuring system by finding another Doppler frequency difference on another base line in a different direction according to this method together with a radial velocity.

Comparing the phase comparison measurement system with the Doppler velocity measurement and position determination system, it has added direct position measurement equipment. The advantage of this type of measurement system is that its accuracy in both velocity measurement and position measurement is very high. However, this kind of measurement system is more complicated. Due to the base line concept, in order to ensure the high accuracy in the measurements of velocity and position, the requirement for the accuracy of the measurement of the base line length is

very high. Its calibration is more complicated. Therefore, this kind of system is mainly used in the measurement of missile accuracy in the main propulsion section.

VII THE MULTIPLE STATION MEASUREMENT SYSTEM

/66

Principle of Continuous Wave Distance Measurement

The measurement of distance by a pulse radar is to modulate a series of pulse signals on the carrier wave and to transmit the wave to the target. The reflected wave is measured with the transmitted wave to determine the time delay, as shown in Figure 3-10. If this time delay is τ , then the distance of the target is

$$R = \frac{C}{2} \tau$$

where C is the speed of radiowave propagation, τ is the time period between the transmitted pulse and the returned pulse, and R is the target distance. In order to ensure the normal function of the radar, the period of pulses is greater than twice the maximum effective range.

When using continuous wave to measure distance, a continuous sinusoidal wave is first modulated on a carrier wave of much higher frequency and then transmitted. After being re-transmitted by the transponder, the carrier frequency is changed and then returned to the receiving station on the ground. The ground receiving station detects the sinusoidal wave modulated on the carrier wave and then measures the phase change between the received sinusoidal wave and the reference sinusoidal wave as shown in Figure 7-1. If the phase is delayed by ϕ , then the distance of the target is

$$R = \frac{\lambda}{4\pi} \phi$$

/67

where R is the target distance, λ is the wavelength of the sinusoidal wave, π is a constant, and ϕ is the phase difference between the transmitted and received sinusoidal waves. However, the measurement of a phase difference is not the same as measuring time. It can only be measured within 360 degrees. For a phase difference greater than 360 degrees, as an example 380 degrees, only a 20 degree phase difference can be measured. From the equation to find the distance, it is clearly shown that if a 380 degree phase difference is measured to be 20 degrees, then a large error in the distance will occur. In the actual measurement, it is completely prohibited. What are we supposed to do? We must ensure that the phase difference does not exceed 360 degrees between the transmitted and received signals at the longest distance in the measurement. To accomplish this, we have to make the wave length of the sinusoidal wave be greater than twice the target distance. For example, if the maximum range of the measurement system is 1000 kilometers, then the wavelength of the sinusoidal wave should be 2000 kilometers; corresponding to a frequency of 150 Hz for the sinusoidal wave. However, one problem is resolved but another one is brought into the picture. In

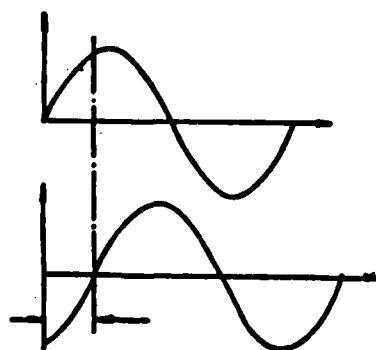


Figure 7-1. Schematic Diagram of phase lag.

measuring the phase difference, the accuracy of phase measurement is somehow directly related to the signal frequency. If the sinusoidal wave signal frequency is 150 Hz for distance measurement, the phase measurement error is 0.1 degree, which causes a distance measurement error of over 500 meters. This is also not permitted. In order to solve this problem, we are imitating a vernier calibre; the number of larger divisions plus the number of smaller divisions is the total length of the measured distance. Hence, in modern measurement system, it usually transmits several distance measuring signals which are proportional in frequency instead of one low frequency signal. This corresponds to a long stick, on the stick there are large scales, medium scales, small scales, and vernier scales. In order to ensure not to have a phase difference greater than 360 degrees and to ensure the accuracy of measurement, this method is adopted. The measured distance can be over thousands of kilometers but the error is only about 10 meters.

/68

Principles of Position Determination and Velocity Measurement

In the previous section, the principle of distance measurement by a single station was discussed. If there are three such stations, as shown in Figure 7-2, to determine a hemisphere for each station then three different hemispheres with different centers must be able to uniquely determine the position of the target in space.

The velocity measurement principle of this system is even simpler. In a multiple station measurement system, the distance measuring signal is modulated on the carrier wave. Hence, in addition to the distance measuring signal, there is carrier signal in the signal. This carrier signal can be used to measure Doppler frequency. The Doppler frequencies obtained independent from three stations can be used to determine the velocity vector of the

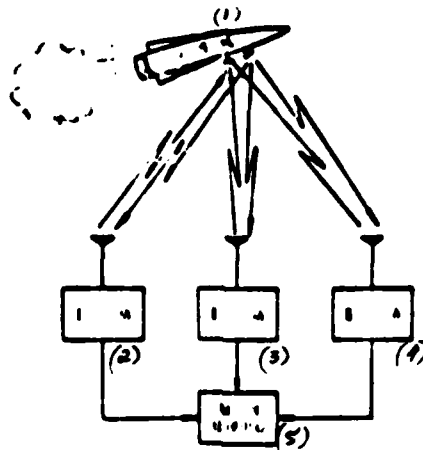


Figure 7-2. Schematic Diagram of the Composition of Multiple Station Measurement System.

Key: (1) Transponder; (2) Station I; (3) Station II; (4) Station III; (5) Data processing center.

target in space using the method described in Section V to complete the velocity measurement and position determination of this multiple station measurement system.

Advantages

The biggest advantage of the multiple station measurement system is to get rid of angle measurement. As we know, for an angle measurement system regardless whether it is a radar or a phase comparison continuous wave angle measurement system, when the accuracy of angle measurement is fixed, then the accuracy in position determination decreases with increasing effective range. This is because, when the distance is very far, a slight error in the measured angle will bring about very large error in distance. As we know "miss by miles and part by miles" is based on this principle. However, with the development of astronautics the spacecraft flies farther and farther. If in the "Ap ollo" lunar landing mission which travels hundred thousands of kilometers, an ordinary angle measurement system by far cannot

satisfy its measurement requirements. In order to solve this problem, the multiple station measurement system was developed. Its measurement accuracy is only determined by the accuracy in distance measurement which is basically unchanged relative to various distance. Hence, the requirements of measuring far away distance can be assured. Therefore, this kind of system is the main method to measure long distance targets. Since this system is previously used to measure far distances, the spacing between stations are far apart, usually several thousands of kilometers. The data from each station must be transmitted simultaneously to the data processing center. This brings about the long distance communication, data transmission and unified command problems. These problems, with the development of science and technology, are not difficult to solve. In addition, this measurement system, no matter how many stations are to be installed, has the same equipment which is convenient for mass production. Therefore, the multiple measurement system, for the measurement of long distance and tracking, is a more ideal measurement system. /70

VIII HOW TO INCREASE THE ACCURACY OF MEASUREMENTS /71

What is Measurement Error all About

When using a stick to measure the length of a straight line, no matter how careful you are, the measured value is different from its actual length. Even if you are a very careful person, and the scale on your stick is accurate and fine enough, the measured value is not the same everytime. Perhaps you may ask if we go to a store to buy 10 feet of fabric, isn't this 10 feet really 10 feet? Yes, it is not really 10 feet. There is a difference between that and the actual 10 feet. However, the difference is very small. In everyday living, people will not notice the difference so there are no bad consequences. Perhaps you may say that the sales clerk repeatedly measures the cloth

and everytime the result is the same. We then have to ask to what degree are they the same. For 10 feet of cloth, if the difference of repeated measurement is only a fraction of an inch, then it is negligible to us. Hence, it is generally considered to be the same. However, if there is a ruler its graduation marks must be close such as a minutely defined scale, and the ruler is used to repeatedly measure the cloth, then the results will not be the same. Of course, in everyday living, nobody will do it this way. It is absolutely unnecessary. However, for the electronic ballistics measurement system, we have to look into these meaningless things because the measurement accuracy requirement of the electronic ballistics measurement system is very high. For example presently around the world when the measured distance is several thousands of kilometers, the accuracy of measurement is on the order of then meters, which means it must be accurate to one hundred thousandth or even one one millionth. For this type of high accuracy, in the measurement of 10 feet of cloth and accuracy is ten thousand times over a mil. Under these conditions, measurement error must be considered. 72

What causes the errors? There are many reasons. Some of them we have already discussed and some of them are unknown. Using the measurement of cloth as an example, if the stick itself is not accurate then how can we expect to accurately measure the cloth! Furthermore, measuring the cloth is done foot by foot. The connection between each foot is different, which will seriously influence the result. In addition, this effect is not the same for different people or the same person at different times. Therefore, the final measured result will show a random fluctuation; sometimes more, sometimes less. Also in measuring the cloth, whether to hold the material tightly or loosely will also cause error. In summary, the reasons to have error are numerous, but they can be divided onto two types. One type is systematic error, such as the inaccuracy of stick described before. No matter when

and what, errors will be created. However, once the degree of inaccuracy of the stick is known, then this error can be corrected. This is similar to our watching the wristwatch which is either too slow or too fast by the same amount every day. People will take the difference off from the time the watch reads. Therefore, systematic errors usually have an order to follow which is also correctable. There is another kind of error which does not have any order to follow. It is sometimes high and sometimes low, such as the connecting point in measuring the cloth by a stick or a watch which goes either too fast or too slow. This type of orderless random variable probable error is called random error.

Since there are two types of errors, we must evaluate the magnitude of the error to determine the success of the measurement. Therefore, we must quantitatively determine these two errors. Now, we are going to use target practicing to explain this problem. In target practice, people all wish to hit the bullseye. However, without rigorous training, the results will be less than ideal. However, even in these undesirable results, these are two situations as shown in Figure 8-1. The first situation is that the results are not very good but it is highly

/73

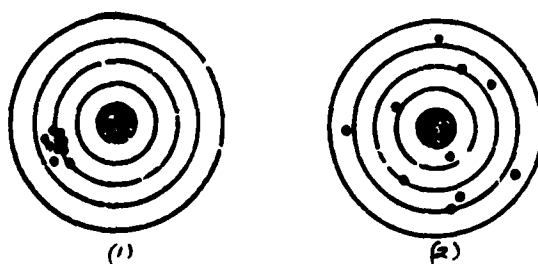


Figure 8-1. Schematics of targets.
Key: (1) (A); (2) (B).

reproducible. The positions of the hit are all in the lower left side. As for the second type, the total results are also not very good and the reproducibility is also very poor. Sometimes it hits the number 9 ring, sometimes the number 1 ring, sometimes left, and sometimes right. The above reproducibility is usually expressed in accuracy, sometimes it is called precision. Whether the results are good is relative to the number 10 ring. In other words, it is a comparison with the number 10 ring. The difference between the final result and the number 10 ring is evaluated as the accuracy. The target A shown in Figure 8-1 has very good precision but low accuracy. The target B in Figure 8-1 shows poor precision and accuracy. To improve the accuracy of the former is easier than the latter because the former may have a defect in the gun itself or the shooter has a habit. Once these problems are resolved, good results can be obtained. As for the latter, diligent train is lacking. Therefore, an outstanding shooter must hit the target with high precision and accuracy. These two concepts are inter-related and also mutually distinguishable.

For a complicated electronic ballistics measurement system, in measuring the target in space, the same two types of errors exist. In addition, more and complicated factors are affecting the measurement accuracy. Among them, some have already been identified, but some are still unknown. For those identified errors, some of them are minimized but others there is nothing one can do about. However, as a whole, the main factors affecting the measurement accuracy are clear. To reduce the effects of those factors, large amount of error has been spent and significant results have been obtained. The following is an introduction to the major factors affecting the measurement accuracy and methods used to overcome the effect of those factors.

/74

Ground Survey Error

A guided missile takes off from the launching site; after a long journey, it lands in the pre-determined test area. A satellite after launching begins to rotate around the earth. In the entire process, it is desirable to monitor their whereabouts to facilitate the continuous measurement of their trajectories and to analyze their flight conditions. Can we rely on one station

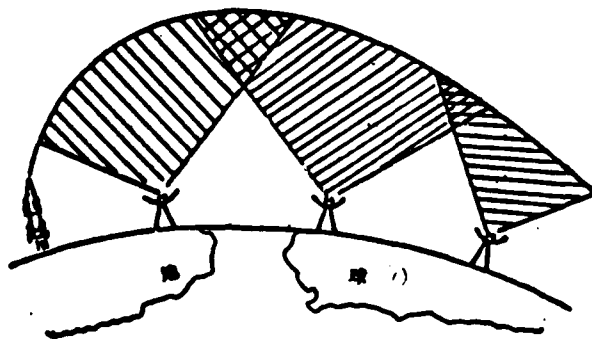


Figure 8-2. Schematic diagram of multiple station relay measurement.

Key: (1) Earth.

of equipment to accomplish this mission? The answer is negative. Based on the reasons stated before, a single station and a measurement system can only have limited time of tracking and measurement. In order to solve this problem, it is necessary to set up a series of measurement stations along the ballistics or trajectories as shown in Figure 8-2. In order to centralize the use of data measured by individual measurement stations, the usual method is to establish a right angle coordinate system using the launching site as the origin. It is necessary to determine the position of every measurement station in that coordinate system. To determine these positions, it is the duty of ground survey. Apparently, if these positions cannot be determined accurately, then it is impossible to accurately measure the

75

positions of targets in space. With the development of the astronomical industry, the flight to the moon as an example, it requires many observation stations across the world. For tracking spacecraft, these stations usually are located in all the continents. Therefore, the requirement for ground survey is getting higher. In order to minimize this error, now ground surveying satellites are widely used to calibrate the locations of the observation stations.

In addition to the above mission, ground survey in the three measurement systems introduced above has another function. These systems do not operate on a single station mode. At least three stations are required to complete the velocity measurement and position determination of target in space. Between the stations in a system, there is a position determination problem. For example, in the phase comparison measurement system, we use the base line length as a constant. In fact, due to the error in ground survey, the length of base line has a certain degree of uncertainty and consequently the measured angle has some error. In order to reduce this error, when measuring the base line, very stringent requirements are imposed on ground survey. For example, when measuring a base line of several tens of meters, the allowable error is a fraction of a millimeter. For units performing the ground survey, large amounts of studies must be carried out to satisfy the continuously proposed new requirements. If this mission cannot be accomplished, the increasing of accuracy of the electronic ballistics measurement system is subject to certain limitations.

Wave Refraction Error

A chopstick standing straight in water appears to be bent. This is because when light passes through one medium to the other will reflect and refract. The parameter to describe the

refractive properties of light by materials is the index of refraction. When radiowave propagates through various media, similarly refraction also occurs. Due to this refraction phenomenon, when the radiowave passes through the ionosphere, the path is bent as shown in Figure 8-3. Due to the curved path, obviously, /76

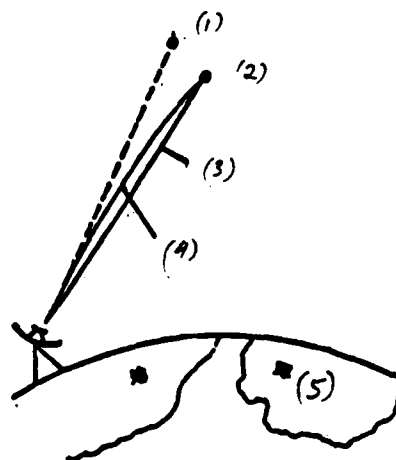


Figure 8-3. Schematic diagram of error produced by refraction. Key: (1) Visual position; (2) Actual position; (3) Propagation path in vacuum; (4) Refracted path; (5) Earth.

the measured distance R is no longer the actual distance. Therefore, error is produced. Due to the curvature of the path, the angle pointing to the target becomes the position pointed by the dotted line. Therefore, error occurs in the position. Due to the error created by refraction, the original position of the target becomes the visual position after calculation. The magnitude of this error as related to the frequency. In general, the higher the frequency, the smaller the effect becomes. In order to reduce the effect of this error, present day measurement systems use higher frequencies.

It is not sufficient to merely rely on the selection of higher frequencies to reduce the error created by refraction. In order to solve this problem, people spent a great amount of effort to study the propagation characteristics of radiowave in the ionosphere and to study the laws producing this refraction phenomenon. It is known through studies that the major reason for causing the path to bend is because the refractive index varies along the height of the ionosphere. Furthermore, the characteristics of the ionosphere vary with time and season. Whether it is capable of reducing the effect of radiowave refractive error, the key is not whether it is able to find the relation between the index of refraction and these factors. Through large amounts of experiments and research, the key is to find some regularities and use them to correct most of the error caused by refraction. The secret of nature can only be gradually learned but there is never an end. Thus, the correction to refractive error can only be continuously studied and improved. Through the hard work of workers in radiowave sciences, it is possible to correct most of the errors in this area. Under this condition, to consider the effect of refractive error, it is only necessary to consider the residual error after correction. /77

The magnitude of the residual error is mainly dependent on the availability of the local weather information and the timing of the correction. Within a certain region in the area of the measurement system, the more and complete the original weather information on relevant ionosphere characteristic is available, the better understanding can be obtained with respect to the law of refraction in the ionosphere, the more accurately a mathematical relation - mathematical model can be written. To have an accurate mathematical model is the basis of conducting correction for radiowave refractive error. Timing is the period between the required original data and the measurement time after the mathematical model is established. Under conditions that the

requirements are stringent, the investigation on the ionosphere and the measurement of the ballistics should be carried out simultaneously to provide the best corrected results. However, the concurrent processing of large amounts of data will require much more in terms of computer volume and speed.

Instrumentation Error

In addition to the two errors above, which have higher effect on the accuracy of the electronic ballistics measurement system, the error of the instrument itself is also an important factor. Its error is similar to the case that the stick itself is inaccurate when measuring cloth. Hence, the magnitude of instrumentation error itself is the basis for assuring accuracy of the entire measurement system.

As described above, a measurement system is composed of many parts. Each part is susceptible to mistakes. All these errors consist of two parts; one is the random error due to "thermal noise", and the other is the systematic error caused by environmental conditions, time, or other factors.

78

In order to reduce "thermal noise" error, it is possible to use two methods. One is to raise the transmitting power, which makes the signal power higher than the noise power to reduce the effect of noise and decrease the random error caused by it. However, this method is subject to some limitation because it is impossible to increase transmitting power indefinitely. In addition, with increasing effective range, this problem cannot be thoroughly resolved. Therefore, it is necessary to adopt the second method, which is the relevance receiving method mentioned in the receiver section in this book. This method involved the extraction of relatively "clean" signal from the "buried" signal to the extent possible, to reach the objective of reducing random error.

To reduce the systematic error, the most reliable method is to study the law of variation of systematic error with environmental factors such as temperature, time, etc. To find this law, it is possible to subtract this error from the measured results. For example, when we check the time on one watch against the Beijing station, if we have already known that the watch is slow by one minute a day, then all we have to do is to look at our watch and add the slow time to it if we can accurately know the time. However, in studying systematic error, we must be able to handle the governing laws which is not an easy thing. Frequently, it requires tremendous effort. With the increasing level of research equipment, great results were obtained in studying the mathematical treatment method of random error. Hence, random error can be made very small. At this time, systematic error becomes the major enemy affecting the accuracy of the measurement system. It is an urgent matter to study the variation laws of systematic error.

Time and Speed of Light Errors

It was discussed in the ground survey section, the measured data from each measuring station must be transformed into one coordinate system. For unity, except the station address, the unification of time is also important. During war times, in order to attack at a unified time in the war, the commanders must synchronize their watches. Without a unified time, unimaginable consequences may result. In ordinary living, in order to have a unified time, we also synchronize our watches with Beijing time. For the measurement system, this problem becomes more important. Without a unified time, the measurement results are meaningless. For example, for a satellite moving in orbit, if its velocity is 8 kilometers per second and the times at the two measurement stations differ by one millisecond, this term only will cause an error in distance measurement by 8 meters. This error is obviously not allowable. Hence, the synchronization of time, for measure-

/79

ment systems several kilometers apart, is a very important problem. In order to solve this problem, some countries established standard time stations using low frequency to transmit to far away distance to satisfy the synchronization requirement of the measurement stations.

In addition to synchronization of time, the speed of light is an unseparable parameter for any measurement system. Usually it is considered to be 300,000 kilometers per second. Actually, the propagating velocity of light is not this value. If we use this number to derive other required quantities, some error must be created. Hence, the experts especially studies the actual propagating speed of light. There are many results. For an ordinary measurement system, the commonly used value is 299,792.5 kilometers/sec. The error of using this value is negligible.

From the above description, we can see that to develop a good electronic ballistics measurement system requires knowledge of various sciences. In order to raise the accuracy and to combat various errors, lots of effort was spent and great results were obtained to reach very high level of standard. To further improve on the present basis is becoming more difficult. It often requires huge effort and the results obtained are not very significant. However, new missions require the continuous raising of accuracy; this is a paradox. The best method to solve this problem at this time is to use mathematical methods to consolidate all the data to improve the accuracy.

Consolidated Use of Data and Data Processing

/80

When we measure a length, if it is required to be more accurate, then the usual method is to repeat the measurement several times and finally take the average value of these measurements as the final measured result. In reality, it has been

proven that the larger the number of repeated measurements the more accurate the final average value becomes. This is the simplest data consolidation and data processing method, which is also the most basic method. For a fixed length we can carry out repeated measurement; but for a target in space we cannot do it because the target is in motion and the measured quantity varies from time to time. Under this condition, how do we improve the accuracy of measurement through mathematical methods? We must use many installations to measure simultaneously. The result is the same as repeated measurements. Presently, it is very common to use this method to increase the accuracy.

As mentioned before, with the manufacturing standard of the equipment and the studies of mathematical methods as described above, random error has been reduced to a very small level. The main obstacle affecting the improvement of the accuracy of the electronic ballistics measurement system is switched from random error to systematic error. How do we eliminate or reduce the effect of systematic error? The simplest method is to find a set of measurement equipment with higher accuracy than that of the measurement system to compare. This is similar to our elimination of the systematic error of a watch by checking with the radio station time once a day. However, the accuracy of the electronic ballistics measurement system has been very high. To find a better system is difficult. For that, a mathematical method is used to solve an optimum trajectory, on the basis of the mathematical model development in studying systematic error, using the extra data of the measurement to compare with the measured trajectory in order to eliminate or reduce the effect of systematic error. This method allows the accuracy of measurement to greatly improve on the original basis. This is the widely used "Optimum Ballistics Estimation" method.

The Establishment of Measurement Control Network

The various ballistics measurement systems are developed along with the development of rockets, missiles, and astronautical industries. Initially, the measurement systems were developed correspondingly to specific requirements based on the emission. At the beginning, optical measurement systems were used. Then, radar systems came along. Finally, various continuous wave ballistics measurement systems followed. For example, there are measurement systems for measuring the main propulsion section; there are measurement systems tracking the orbits of satellites; and there are measurement systems measuring deep space manned flights. However, they can only accomplish their own duties. They are really "railroad cops; each manages their own section". Furthermore, each system has different frequency and requirements. The range of usage is narrow and it is inconvenient to manage, which causes significant waste. Under these conditions, people are forced to study the new problem - how to greatly utilize the effectiveness of each equipment; how to reduce the number of types of equipment; how to ensure the centralized control of the various measurement systems. Besides, each mission must be equipped with remote measuring and remote control systems in order to continuously issue commands to the target in the air according to a pre-arranged plan, to accurately accomplish the flight mission without any mistake. However, remote measurement and remote control are also a set of huge and complicated equipment. If it is possible to consolidate the three missions in one equipment, it is then possible to save manpower and materials significantly. Is it possible? Through theoretical research, realization is a possibility. Such a control measurement network has been in existence.

What is a control measurement network? It is to combine a number of measurement systems or measurement equipment together for centralized command and control. During the mission, they compliment each other, match each other and the data are processed centrally. To do so, we must unify the frequency in the measurement control network. It has multiple functions. It is not only responsible for measurement, but also for receiving the remote measurement data, and transmission of remote control commands. For the measurement control network for manned spacecraft, it must also include the transmission of voice signals, television signals, etc. For example, on the American "Apollo" lunar landing mission, a "unified S band system" was developed to accomplish the above missions. The development of electronic ballistics measurement and control has reached a new era. In addition, the measurement control network can carry out tracking measurements at different targets. For example, it can complete the measurement of the main propulsion section, the measurement of the orbiting section, and the measurement of manned spacecraft, etc. To do so, we have to ensure the suitability of the equipment to the various duties and the rational geographic distribution. For example, an American astronomical tracking network has 19 ground stations, an observation vessel, and a control center. These stations are all over the US mainland, European continent, and Australia to complete a global tracking, measuring, control and data acquisition and transmission. It can be imagined that such a large measurement control network has a very complicated communication and data transmission system in addition to the measurement systems itself.

Data Relay Satellite System

As discussed before, in order to continuously obtain the necessary data, to carry out measurement and control on satellites, and to establish uninterrupted communication connection, we must set up a global tracking measurement control network. With the

appearance of manned flights, to ensure the safety of the astronauts, the necessity to establish a measurement control network is ever higher. However, despite the large amount of work described above, for the measurement, tracking, and control of orbits near the earth, there are still serious problems remaining. This is that the coverage area is too small. In other words, the time for tracking, measuring the spacecraft, and coming into contact with the earth is too short, which only covers a small portion of the entire orbiting period. This is a serious problem for manned flights. One of the American measurement control networks, although with all the stations installed all over the world, can only provide 27% of the coverage area. To solve this problem, one way is to increase the number of stations on earth. But, it is often impossible in practice. Because, the additional stations can only be established outside the country. Furthermore, it is limited by geographic conditions. At some places it is possible, while in other places it is impossible. Besides, not all countries allow the establishing of a station by others. Some of the stations must be set up in the ocean. It requires the construction of observation vessels. There are great problems from economical and management points of view. /83

In order to solve this problem, a new concept appears which is the data relay satellite system. The system uses two satellites on synchronous orbits with a radial phase difference of 130 degrees. They are relay stations with respect to ground equipment, satellites, and spacecrafts. These relay stations connect the lower orbit satellites and manned spacecrafts with the ground tracking measurement stations. The communication and control signal from the ground facilities are transmitted to this "relay station", and these "relay stations" then re-transmit these signals to the lower orbit satellites and spacecrafts. Conversely, the data signals of spacecrafts and satellites are transmitted to the "relay stations" and then from the "relay stations" to the ground facilities. What is acting as the "relay station"? Synchro-

nous orbit satellites are best candidates to fill this role. After using this new system, the tracking time of lower orbit satellites and spacecrafts can be increased to 85%. For medium orbit satellites, it can be increased to 100%. By using this system, it is possible to continuously track and monitor satellites and spacecrafts to maintain communication contact. It not only ensures the safety of the astronauts, but also eliminates the need to expand ground stations. It is easy to manage and it lowers the cost. This kind of system has a bright future especially for future manned flights.

Measurement of Cruise Missiles

The cruise missile is cheap to make, has high accuracy, and is /84 capable of flying very low at an altitude of several tens or hundreds of meters. Therefore, it can penetrate radar defense and quietly enter and hit the target. Based on the above advantages, the cruise missile which has been put away for many years, again becomes the "favorite" in modern day arsenal. With the emerging cruise missile, a new subject was brought into ballistics measurement. The most important thing is that the altitude of the cruise missile is too low to be detected by existing measurement techniques. The precise measurements of the position and velocity of a cruise missile remain to be a problem unresolved. Why can't we accomplish this measurement? First of all, because the earth is an ellipsoid and the radio wave is transmitted as line of sight. Secondly, measuring antenna has a fixed band width. In order not to let the wave "hit the ground" (otherwise great interference will be brought about), in normal working condition there is a minimum angle of inclination. Therefore, it is not easy to detect a cruise missile as shown in Figure 9-1. To solve this problem, one of the two following methods can be used. One is the use of an airborne tracking measurement system as shown in Figure 9-2. This system moves the entire measurement system on board of an airplane

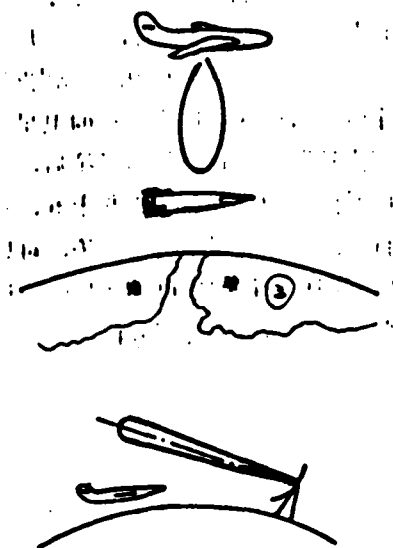


Figure 9-1. Entrance zone of the cruise missile.

Fig. 9-3. Schematic diagram of the airborne measurement.

Key: (2) Earth



Figure 9-3. Schematic diagram of system detection of low altitude target by laser radar.

to monitor from up to down. Then, the first problem described before is overcome. The use of this method has high mobility and flexibility. However, there are disadvantages also. Since the earth is a very good reflector with a large reflection area; hence, the returned signals received by the antenna contain high power ground contaminated wave in addition to the reflected wave by the cruise missile. How to extract the signal of the cruise missile from the intense ground contaminated signal is a key technology for this system. Another method is to use laser radars to form a ground monitoring network. The biggest advantage of laser radar is that the wave beam can be made very narrow. Thus, the ground hitting problem of the beam can be avoided. The antenna can be aimed directly at the target as shown in Figure 9-3 and the problem of measuring low flying cruise missile is then solved. Since the range of laser distance measurement is only about 20 kilometers, in order to ensure the measurement of cruise missiles, it is required to set up many stations. Furthermore, laser radar is affected by the weather more significantly.

Measurement of Re-entry Section

The measurement of re-entry section has two meanings. One is the measurement of the target characteristics of a re-entered target. With the development of anti-ballistic missile weapons, offensive missiles have a problem to penetrate the defense of the other side. The usual method is to launch interference before the missile reaches the target. The interference can be aluminum foils or a simulated target reflector, etc. With penetration, there must be anti-penetration. The key to anti-penetration is to identify the target. Which are the interference targets and which are the real targets. This problem to a great extent relies on the study of the characteristics of the target. In order to study the target characteristics, we must use a pulse reflection working system. Hence, the study of the target characteristics of the re-entry section is carried out by pulse radars.

The second type of measurement in the re-entry section is the measurement of ballistics at the re-entry end. This measurement has a great effect on the study and improvement of the accuracy of the missiles. However, this type of ballistics measurement brings some new problem to the system. The most important one is the "ionization shield" problem. When the missile re-enters the atmosphere, due to its high speed, heat is generated from friction with the dense atmosphere to create a high temperature of several thousand degrees at the surface of the missile. At this high temperature, the air surrounding it is ionized. The ionized gas corresponds to a thick protective clothing for the missile, so that the lower frequency radiowave cannot penetrate. This is the origin of "ionization shield". In order to penetrate this "shield", we must use higher frequency radiowave. Study shows that only millimeter wave - wavelength under several millimeters can penetrate. The original equipment cannot handle the job anymore. In addition, when re-entering, the speed of the missile is very high and the acceleration is large. Hence, it brings a lot of problems to the

capturing and tracking of targets. These new problems will have to be resolved.

Concluding Remarks

The book attempts to provide a general overall introduction to the electronic ballistics measurement system to the large number of readers so that they will have an initial understanding on this new technological science to broaden their views, to increase their knowledge and, to create interest in this science and to contribute to the four modernization goals for the country. Whether this objective can be achieved, the readers can provide a positive or negative answer once they read the last page. In the writing process, the author felt that it is a difficult task which became even more difficult towards the end. This is because under each small heading in the book, there is a special technology with hundreds and thousands of people working on the problem. For example, the standards of time and frequency, the propagation of wave, the study of relevance receiving ---etc. Thus, it is very difficult to provide a clear concept of these things within a few pages. Furthermore, in order to expand the number of readers, it is not possible to use complicated mathematical formulas which become more difficult.

In spite of these difficulties, through this book, it is possible to explain the following problems:

(1) Any new technology cannot be separated from its theoretical basis. The flight of missile cannot be separated from laws of mechanics; the theories of radiowaves cannot be separated from the basic laws of electromagnetic fields; the complicated mathematical data treatment originate from the ancient least squares method. Therefore, to study the basic sciences and to have a fine foundation is the first step to pioneer any new science.